CATHODE-RAY
TUBES

CATHODE-RAY TUBES

BY

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TRANSLATED FROM THE GERMAN

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PREFACE

UNTIL a few years ago the cathode-ray tube was comparatively unknown. It was only through the efforts of Dufour, Rogowski and his pupils, Gabor, Mathias, Knoll, and their colleagues, to make it suitable for the special demands of high-tension work, that it achieved due importance in this branch of electricity. The cathode-ray tube was sometimes used in low-tension work for research, though more often for teaching purposes, on account of the difficulty of handling, and the complication of accessories, the discharge chamber being generally used in conjunction with vacuum pump equipment.

The adoption of evacuated tubes with hot cathodes for the production of slow electron rays by Wehnelt, Westphal, Zenneck, Johnson, and others, first gave rise to a considerable simplification of apparatus. Complete success did not, however, result from this alone because the spot was not bright enough for practical requirements on account of the low electron velocity and insufficient ray intensity. It was the perfection of evacuated electron-ray tubes with hot cathodes and gas-filling suitable for anode voltages of several thousands, as well as the production of complete main units, which resulted in the evolution of instruments suitable for general use and capable of meeting the strenuous demands of electrical technique.

Simultaneously with, or perhaps even previous to, the development of the cathode-ray tube into a scientific measuring instrument, various important accessories and a large number of circuits and methods of use in measurement were brought out. As a result, the cathode-ray tube came to be used in all spheres which involved electrical measurement or the recording of oscillations. It will be readily appreciated that the methods and accessories used in the solution of special problems vary considerably, according to the requirements of individual cases. In spite of these differences, the different arrangements have certain important components which are common to all of them. The cathode-ray tube is used in all the applications. Chapter I of this book is devoted to its theory and construction.

Chapter II deals with those accessories of the cathode-ray tube which are most frequently used. These include, for

intance, the mains equipment, the pre-amplifier for increasing the sensitivity, the time deflection apparatus, and photographic recording equipment.

In the remainder of the book are discussed the uses of the tube in specialized problems.

The Author believes that this arrangement will result in an ordered presentation of the subject, which covers a wide field.

The first two sections are suitable for those readers who are anxious to develop their own measuring circuits, to adapt circuits to current problems, or to build up *ab initio* new methods for their own particular requirements. For those who are perhaps less familiar with measuring technique, and who work out problems which constantly recur, a third section is provided, and in it the author has included as far as possible all the applications known to him. In this section, therefore, principles are first discussed, and then particular attention is paid to practical applications, design, and characteristic results.

An exhaustive consideration of the use of the cathode-ray tube in television is given in the last section. The development of the cathode-ray tube during the last decade has in a large measure established its importance in this field, which industrially has a promising future.

I have to thank Dr. Knoblauch for his collaboration.

MANFRED VON ARDENNE

LICHTERFELDE OST,
JULY, 1933.

PREFACE TO ENGLISH EDITION

Although only about three years have passed between the writing of the manuscript and the preparation of an English edition, it has been found necessary to re-write or alter considerably a large portion of the book, in order to bring the contents into line with the enormous progress which has been made in the technique in the meantime. It is unusual for progress to be made in fundamentals in such a short time in a sphere which had its beginning about thirty years ago. The explanation of this fact is to be found at the end of the preface to the first edition. The intensive development work which has been carried out on the cathode-ray tube during the last few years in many laboratories, in view of its importance in television, has resulted in the high-vacuum tube constructed on electron-optical principles superseding the tube operating with gas focusing.

The change-over to the vacuum tube has enabled the problem of life and stability of performance to be solved satisfactorily. The almost complete removal of anomalies in deflection, the improvement made in the relation between the spot and the surface of the fluorescent screen with reference to television and the creation of systems which provide for almost perfect control of the ray, i.e. variation in brightness, may be described as important steps forward. The progress referred to is equally advantageous to television technique, sound recording, and measurement with the cathode-ray tube. In the realm of measurement, this progress has resulted in an enormous increase in precision. The measuring accuracy of a modern high-vacuum tube is very little less than that demanded of a d.c. indicating instrument. The fact that the deflection sensitivity is almost completely independent of frequency and that it is possible to calibrate by means of d.c. voltages or currents may be regarded as an important advance. Considerable alterations of accessories in circuits for time deflection have become necessary. In part these alterations are due to simplification and improvement, although the remainder have been made necessary in order to make deflecting apparatus suitable for the special requirements of the high

vacuum tube. The re-writing of the section on the use of the electron-ray tube for television transmission has not been undertaken since the author has discussed this subject in considerable detail in the light of present-day experience in his book entitled *Television Reception*, which was published in 1936. Nevertheless this section has been greatly extended and completely revised with the object of including older contrivances which are not employed in modern television but which include interesting solutions to subsidiary problems of general importance, such as velocity modulation, as well as the more recent devices.

The completion of the volume has naturally been delayed by the translation until the end of 1937. The rate of development previously mentioned has not decreased since 1935. It would be necessary to carry out a complete revision of the book in order to bring it into line with present-day practice, especially in respect of tube construction and certain other apparatus. The author has refrained from doing this because he is of the opinion that the main sections, and particularly those portions of the book dealing in detail with the use of the cathode-ray tube, still hold good.

MANFRED VON ARDENNE

LICHTERFELDE OST.

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CATHODE-RAY TUBES

CHAPTER I

THE CATHODE-RAY TUBE

I. General Notes on Cathode-Ray Tubes

The extraordinarily low inertia of cathode rays, which makes possible the recording of transient phenomena in research on electrical oscillations, has made the cathode-ray tube indispensable in the sphere of high-frequency technique.

Its initial development was mainly concerned with increasing the speed of traverse of the electron beam. The tracing speed is that at which the spot formed by the electron beam moves across the screen or photographic plate. The maximum tracing speed attainable is that at which the spot is just perceptible, either directly or indirectly. Very successful research during the last few years has resulted in the production of the high-frequency high-tension oscillograph, which, operating at a traversing speed of over 50 000 km./sec. is capable of recording any transient phenomena in modern electrotechnics. Very high electron velocities were encountered during the period of development of a high-frequency recorder, and for cathode rays having an electron speed approaching the velocity of light it is possible to traverse the path in the deflecting field in a period which is short compared with the duration of the phenomenon under investigation. In this connexion the recording of transient phenomena in conductors presented the greatest difficulties. On the other hand, it was realized that this instrument provided the only means of investigating high-speed electrical phenomena, and consequently the erection of costly equipment for high-tension oscillographs was warranted.

But during the last few years, a second form of cathode-ray tube has been developed simultaneously with, but independently of, the type with which success was obtained in research on short time phenomena. For low and medium frequencies, the older types of cathode-ray tubes which had badly-focused low intensity spots, and presented difficulties in photographic

recording, had little prospect of competing with mechanical oscillographs which already existed in a perfected state (Duddell oscillograph, string galvanometer, etc.). Conditions altered fundamentally, as soon as it became possible to obtain sharp and bright spots at low voltages with simple apparatus. The hot cathode and the discovery of gas-focusing and the development of electron-optical systems and their use in high-vacuum cathode-ray tubes showed that progress was being made towards producing the low current oscillograph.

To-day, low voltage cathode-ray oscillographs in the form of easily handled glass discharge tubes are being manufactured, and they can be operated with the aid of the simplest accessories. Low anode voltages—some few hundred up to 5 000—are easily produced with the aid of small rectifiers; the high sensitivity at low anode voltages makes possible the investigation of voltages such as those which occur in l.t. work; and the fact that pumps and vacuum controls can be dispensed with results in a great simplification of apparatus and facilitates the use of the tube. In consequence, the use of the cathode-ray tube for low voltage work has increased enormously during the last few years.

1. **Fundamental Principles Involved in the Use of Electron Streams for Recording Oscillations.** The technique of oscillography with cathode rays is based on the following properties of the rays—

Rectilinear propagation.
Capability of deflection.
Power of penetration.

By the aid of Fig. 1 which is a schematic diagram of a cathode-ray tube, we will examine these properties. Fundamentally, there are three distinct parts of the tube—

The discharge space.
The deflection space.
The recording space.

The electrons which form the cathode rays are produced in the discharge space. In Fig. 1 this area is shown bounded by a disc A, the anode or *gun*. Details of the way in which the rays are produced will be given later but the general relation between accelerating voltage and electron velocity may be mentioned here. The electrons leave the cathode with a velocity which

at first rises rapidly and then at a slower rate with the accelerating voltage. The relation between anode voltage V, electron

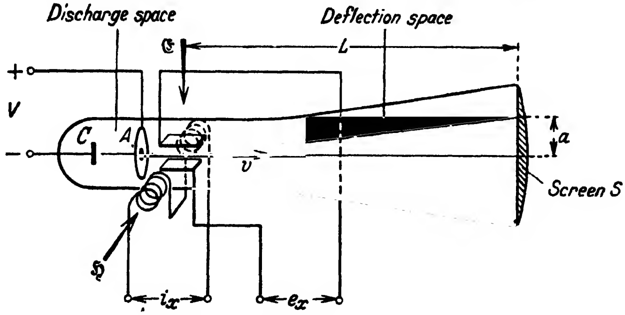


FIG. 1. DIAGRAM OF SIMPLE CATHODE-RAY TUBE

velocity v, mass of an electron m_0, and electronic charge e, is given by the relation

$$m_0 v^2/2 = e\mathrm{V}. \qquad \qquad (1)$$

The work done by the anode field is converted into the kinetic energy of the moving electrons. Taking into consideration the numerical values of the quantities involved the equation becomes

$$v(\text{km./sec.}) = 593\sqrt{V}\ (\text{volts}) \qquad (2)$$

In Fig. 2, showing the relation of electron velocity to anode

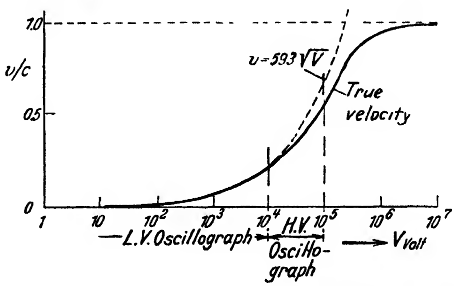


FIG. 2. VELOCITY AND ANODE VOLTAGE

voltage, the dotted line corresponds to equation (2). The velocity of the electrons for voltages up to 10 000 V. is less than one-fifth the velocity of light. These are the conditions under which low-tension oscillographs are operated.

In the case of voltages up to 100 000, such as are used with high-tension oscillographs, the actual speed of the electrons does not increase according to the relation given—but at a lower rate. As the speed of the electron approaches the velocity of light, its mass increases according to the Lorentz-Einstein relation

$$m = \frac{m_0}{\sqrt{[1 - (v/c)^2]}} \quad . \quad . \quad . \quad (3)$$

At one-third the velocity of light, i.e. with an accelerating potential of about 50 000 V, m is 5 per cent greater than m_0 and increases further at higher voltages. This relation, which is of

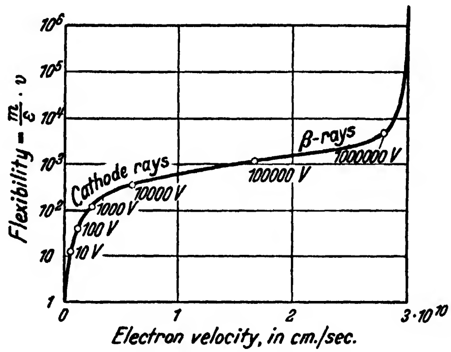


FIG. 3. VARIATION IN FLEXIBILITY OF CATHODE RAYS WITH INCREASING VELOCITY

interest in connexion with the deflectability of the rays, i.e. the sensitivity of high voltage tubes, is expressed even more clearly in Fig. 3—magnetic deflection.

It is possible, by methods which will be discussed later, to control the electrons in the discharge space so that their individual paths remain parallel with one another. In many forms of construction the discharge space can be sealed off from the adjoining deflection area by metal foil through which the high speed electrons penetrate. The power of penetration increases as the fourth power of the velocity, i.e. the square of the accelerating voltage. Fig. 4 shows the relation more clearly, and according to Lenard.[1] the absorption depends entirely on the density of the medium to be penetrated. This explains why an aluminium or beryllium window is particularly suitable.

After passing through the discharge space, the cathode rays enter the deflection space, this being the region in which the electrons are under least restraint. The diameter of the electron stream in this space must be kept as small as possible. An

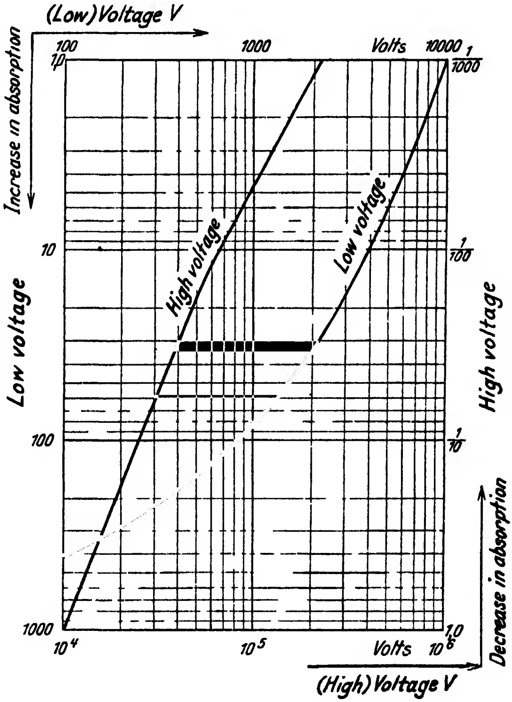


FIG. 4. THE RELATION BETWEEN ABSORPTION AND ELECTRON VELOCITY

increase in diameter of the stream occurs through diffusion of the electrons in contact with the gas molecules, but this cannot happen if the vacuum is sufficiently high.

A further cause of diffusion or de-focusing is the mutual repulsion of electrons in the stream. The external field, the time constant of which is to be recorded, influences the ray in the deflection space. This field can be established as an electrostatic one between two short condenser plates or as a magnetic field by means of deflecting coils. A change in direction occurs at the end of the path and the magnitude

of this deviation is directly proportional to the length of the path.

At the end of the path, the registration of the tracing point takes place either visually or photographically. Only the high velocity electrons produced in high-tension oscillographs are, on account of their penetrating power, suitable for recording directly by photography.

The photographic plate or film can be fitted in a special recording chamber inside the tube (internal photography) or can be affixed to a permeable seal or Lenard window (contact photography). Another method consists of fixing the photographic plate direct to the reverse side of a thin transparent screen so that the whole acts as a seal to the oscillograph and keeps out air (screen contact photography). In the case of low-tension oscillographs in which low electron speeds are involved, the tracing of the curve is made visible on a screen and generally photographed with camera and lens (photography with camera and lens).

2. **Production of Cathode Rays.** (A) ION TUBES. Following upon the explanation of the deflection of rays given in the previous section, we will now examine the possible ways in which such rays can be produced.

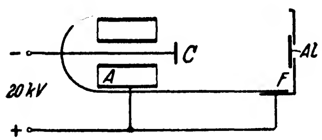


FIG. 5. DISCHARGE TUBE WITH COLD CATHODE

Discharge tubes in which cathode rays are produced are divided into types having cold or hot cathodes. The cold cathode or ion tube was historically the first development. When conceived it represented a further development of the glow discharge tube, and its shape was as shown in Fig. 5, the result of the work of Lenard and Goldstein. An aluminium plate at *C* serves as the cathode. The anode can be placed where desired; in Fig. 5 it is shown as a tube at *A* behind the cathode. An aluminium window at *F* seals off the tube from the atmosphere and enables measurement of the rays to be made outside as well as inside the discharge space.

At a pressure of about 10^{-2} mm. mercury in the discharge tube, a d.c. voltage between 20 and 100 kV. is applied between the electrodes. A spontaneous glow discharge takes place, electrons are ejected from the cathode by the impact of positive ions and these again produce further positive ions by disruptive

collision. The electrons move in a straight line inside a narrowly circumscribed blue illuminated beam which becomes more divergent as the distance from the cathode increases. They attain their maximum velocity at a distance of a few millimetres from the cathode, i.e. almost the whole drop of potential takes place over this short distance. A decrease in pressure practically extinguishes the discharge. Of course, a glow discharge can be produced with lower anode voltages in cold cathode tubes having pressures higher than 10^{-2} mm. mercury, but cathode rays of lower velocity produced in this way are not confined to narrow beams—they spread out in all directions from the whole surface of the cathode. Such a tube would, therefore, be unsuitable as a cathode-ray oscillograph. These facts show clearly the necessity of using the highest anode voltages with

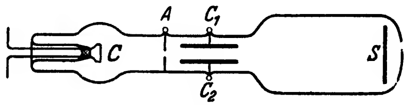


FIG. 6. SIMPLE HOT CATHODE TUBE WITH GAS-FILLED DISCHARGE SPACE (WEHNELT)

ion tubes. The cold cathode tube is essentially a high voltage instrument.

(B) HOT CATHODE TUBES. The introduction of a hot cathode (Wehnelt)[(2)] alters materially both the physical construction, and also the conditions under which the tube must be operated. Since an incandescent metal provides a source of electrons, it would seem possible, at first sight, to dispense with the gas-filling of the cold cathode tube entirely. Actually this was done during the development of hot cathode technique, but the inclusion of the hot cathode in gas-filled tubes has advantages.

The emission of thermions from the neighbourhood of the cathode considerably reduces the cathode potential drop. It is possible, therefore, to reduce the anode voltage considerably —to a few hundred volts. Fig. 6 shows the Wehnelt tube as an example.

II. PRODUCTION OF NARROW BEAMS OF CATHODE RAYS

1. **General Considerations.** So far we have discussed only the physical processes in the production of cathode rays. Nothing has been said about the formation, configuration and

structure of the discharge path. The control of these factors forms one of the most important tasks in the construction of scientific oscillograph tubes. The solution of these individual problems will be shown later by examples of practical cathode-ray tubes. For the moment, we will discuss the physical basis of the methods used to obtain definite beams.

A sharply focused stream of electrons is required in the deflection space and on the screen of the tube.

When it enters the deflecting space, the stream comes under the influence of the transverse deflecting field, which must produce an equal effect on all current paths in the stream and must therefore be larger than the dimensions of the ray and uniform in all positions occupied by it.

2. **Ray Concentration.** (A) METHODS. An uninfluenced cathode ray does not retain its initial cross-section owing to diffusion and internal mutual repulsion of the electrons. Diffusion occurs in the presence of gas, becoming greater with increasing gas pressure and decreasing electron velocity. Ignoring for the moment the special laws of the formation of rays—these will be considered in detail later—the ray becomes completely diffused at a pressure of just over 10^{-2} mm. mercury. Even rays produced at 10 000 volts become diffused in air after travelling only 1–2 mm. But internal fields also exist in a high vacuum, and these cause a gradual increase in the cross-section of the stream.

Obviously the effect of mutual repulsion of the charged electrons is greatest on the outer ones and can be ignored for those at the centre of the jet.

(i) *Focusing by Means of Electron-optical Systems formed by Electrodes.* Concentration of the ray can be achieved by the use of electrostatic or magnetic fields. One of the chief conditions for the attainment of high accuracy of measurement with the cathode-ray tube is to have as small a fluorescent spot as possible. Apart from this a spot of a certain constant size is needed for television reception. The size of the fluorescent spot depends on the electron-optical properties of the tube. Although a point source is possible with gas-filled tubes, an approximate point source, real or virtual, can be formed in a high vacuum tube by the use of suitable methods of focusing.

A metal disc with a hole in the centre represents the simplest method of producing parallel rays from a diverging cone of

rays. The rays leave the disc at a divergent angle which, in the case of a point cathode, depends on the relative size of the aperture in the disc and its distance from the cathode and can therefore be made small. This simple method was, in the early days, one of the first employed for the production of closely confined beams. For instance, F. Braun[3] incorporated it in his first cathode-ray tube, and it was also used in the same year by Thomson.[4]

The great disadvantage of this method lies in its low efficiency. Most of the cathode radiation is absorbed by the disc before it can enter the deflecting space and the tracing ray does not receive sufficient electrons. Simply increasing the cathode temperature does not counteract the losses in the disc and

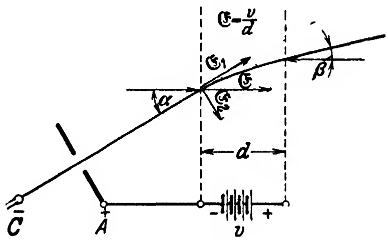


FIG. 7. REFRACTION OF RAYS IN A NARROW CONDENSER FIELD

overcome the difficulty, since the specific emission of the cathode cannot be increased indefinitely. Furthermore, increasing the cathode emission is perforce associated with a corresponding and undesirable increase in anode loading. Fundamentally, therefore, the use of a disc alone is not an efficient arrangement. The object should be to concentrate without loss all the rays emitted from the cathode, even if they diverge, into a spot of well-defined magnitude; in other words, to exploit the whole of the cathode emission. This result can only be obtained by employing auxiliary focusing devices. The formation of images by electron-optical means is one way of doing it. Simple electrostatic methods may be used in forming such images.

A most interesting process has been shown by M. Knoll and E. Ruska[5] and by von Brüche[6], and has been used very successfully in the further development of electron ray optics (Fig. 7). If two parallel metal grids between which there is a difference of potential are interposed in the path of

the ray, the stream will undergo a change in direction unless it is normally incident to the surface of the plates. The *refractive index* of this arrangement can be varied by altering the voltage between the plates. Following this principle, all the corresponding analogous surface effects which occur in optics can be reproduced. For instance, prismatic dispersion is practicable, and is the means by which satisfactory analysis of non-uniform velocities can be made. Fig. 8 shows an interesting convex lens for cathode rays. The lens, which can be used as an anode, consists of two wire grids, one inside the other, and insulated from one another. The potential on the outer grid is less positive than that on the inner one. The electron stream,

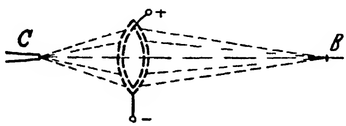


FIG. 8. ELECTROSTATIC "CONVERGING" LENS FOR CATHODE RAYS

therefore, on entering the space between the grids, is refracted towards the axis. Inside both grids the field is uniform and the electron stream is not affected. On leaving the condenser it is again refracted, this time away from the normal. The focal length of this arrangement can be altered at will by varying the voltage, so that an image of the cathode can be formed at any desired distance magnified or diminished as the case may be.

Such electrical lenses represent mechanically and geometrically the exact analogy of optical lenses. Their practical application in the cathode-ray tube, however, involves several serious disadvantages. For one thing, exact adjustment and centring of the parts of the lens, especially when the distance separating them is small, are very difficult to carry out. Furthermore, absorption losses, secondary emission and heating effects appear, and exert a very detrimental influence on the image formed by the electron lens. For this reason, tubular lenses have been adopted for the cathode-ray tube and these have fields, the potential surfaces of which correspond to the refracting surfaces of the optical lens. Even here, the most varied optical systems can be imitated by variation of the tube diameter and potential. Among the various forms of electrostatic-optical arrangements, those known as *accelerating*

lenses are of considerable practical use. In forming images by accelerating lenses, the law*

$$\text{Magnification} = (b/a)\sqrt{(V_L/V_a)} \text{ applies} \quad . \quad (4)$$

where b = distance of image, a = distance of the object, V_L the electron velocity in front of the lens† called hereafter for short the *voltage of the lens* electrode, and V_a the velocity behind the lens (*anode voltage*).

This law shows that only relatively low magnifications can be obtained with accelerating lenses even when the distance of the object is small compared with that of the image. Accordingly the length of the tube can be relatively short when an

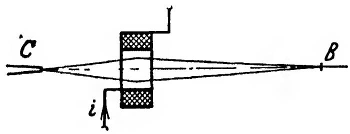


FIG. 9. THE EFFECT OF A FOCUSING COIL

accelerating lens is used, and this is of considerable importance when fitting cathode-ray tubes to receivers or equipment.

Another method of focusing is by the use of longitudinal magnetic fields. A focusing coil, short in comparison with the path of the ray, is wound on a cylinder, the axis of which coincides with the axis of the ray (Fig. 9). The magnetic field of the coil acts on all those electron streams which do not follow the required direction, i.e. the diverging rays, and compels them to follow a deflected path. As Busch has shown, the additional deviation which the electrons undergo, depends on the angle of incidence of the electron streams to the field when they enter the coil. The effect of the focusing coil is, in this case, exactly analogous to that of an optical lens.

At B, the focus of the rays emitted from C, an image of C is formed. This analogy also holds, quantitatively. Busch[7] provided the mathematical proof of the analogy between the focusing coil and the lens, and showed that the optical law

$$1/a + 1/b = 1/f \quad . \quad . \quad . \quad . \quad (5)$$

* See A. L. Hughes, and J. H. McMillen, *Phy. Rev.* 39 (1932), 585; and v. Ardenne, *M. Beiträge zur Elektronenoptik* . . . and *Zeits. f. Phys.*, Vol. 88, p. 254.

† For simplicity, only one lens is always mentioned here, whereas actually accelerating lenses are well known to be composed of two separate lenses of different signs, though separated only a short distance from each other.

is applicable where the focal length of the focusing coil is given by the relation

$$f = \left[\frac{2v}{e/m}\right]^2 \frac{1}{\int_{-\infty}^{\infty} h^2(z)dz} \quad . \quad . \quad (6)$$

$\int_{-\infty}^{\infty} h^2(z)dz$ is the integral of the square of the strength of the magnetic field taken over the whole symmetrical axis. f is therefore dependent on the current in the coil i. A magnified or diminished image of the cathode can be produced in this way at the point B.

Cathodes having large surface areas are essential if low specific emission is desired and large current streams are to be obtained. Sharp spots can be attained with such cathodes only when the image of the cathode is greatly reduced. This reduction can be accomplished with the arrangement just discussed only when the distance between the cathode and the lens is greater than that between the lens and screen. As the distance between the lens and screen should be as great as possible, to secure adequate deflection it is advantageous to reduce the length only when a tube of several metres in length is considered practicable.

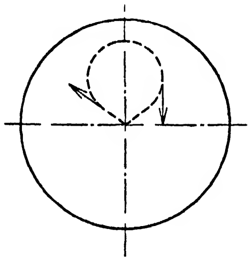


FIG. 10. PROJECTION OF THE RAY PATHS ON A SECTION PLANE

(ii) *Gas-focusing*. In addition to the methods for focusing given above, there is another phenomenon which has achieved importance in practice, as a means of securing the same result.

This phenomenon occurs in gas-filled tubes. It is the so-called *self-concentration* or *gas-focusing*. Its advantage lies in the fact that its operation can be made entirely independent of the position of the ray. Westphal,(8) van der Bijl,(9) Johnson,(10) Buchta,(11) Wood,(12) van Itterbeck,(13) Ranzi,(14) Brüche,(15) and the author, (16) have found that an additional focusing of divergent rays occurs under certain conditions in hot cathode gas-filled tubes in which the pressure is about 10^{-3} to 10^{-2} mm. and the anode voltage 20 to 2 000. It is considered to be due to the ions formed in the cathode stream by collision of the electrons with the gas particles. These ions, by reason of their

greater mass and therefore lower velocity, move more slowly from the centre of the rays than the secondary electrons which are produced simultaneously with them. A positive charge is therefore formed in the path of the ray, and the resultant field restrains the electrons of the cathode stream from tending to deviate from the axis of the beam.

This positive charge is dependent on—

(*a*) The number of ions formed in the ray per second, i.e.—

(i) On the electron stream which in the hot cathode tube is controlled by the cathode temperature.

(ii) On the pressure of the gas and the temperature.

(iii) On the ionizing power of the electrons at their velocity corresponding to the applied anode voltage.

(*b*) On the ion losses per second in the ray. These are estimated from the number withdrawn from the ray owing to recombination of positive ions and electrons.

A very good experiment which confirms the above explanation of gas-focusing was originally carried out by Ende and is illustrated in Fig. 11. The electron beam passes through a

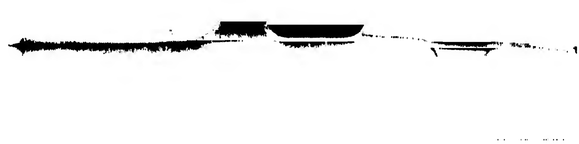


FIG. 11. EXPERIMENT FOR CONFIRMING THE EXISTENCE OF POSITIVE IONS IN THE PATH OF THE RAYS
(*Photo by W. Ende*)

number of transverse electrostatic fields. These are formed between short condenser plates and alternate ones are of the same polarity. A strongly luminous glow is carried over to the negative plates, while the positive plates remain dark. Obviously the positive ions are being drawn from the interior of the beam in considerable numbers and combine with electrons in the vicinity of the negative plates, at the same time becoming luminous from the energy set free in recombination. Measurement of intercepted streams of these positive and negative

ions show that in magnitude they are of the order of 1 per cent of the main cathode stream. Further proof can be obtained from experiments in which the ray behaves differently from what would be expected of a stream of purely negatively electrified particles. Further reference will be made to this when discussing the anomalies of electrostatic deviation and investigating the tracing of high-frequency phenomena with the electron beam.

Another possibility for forming a small fluorescent spot in the cathode-ray tube is provided by the combination of the focusing methods described in the previous sections.* Whereas the combination of magnetic lenses and gas filling does not produce any particular advantages, the introduction of an electrostatic focusing system has a certain signficance, since here a part of the focusing is taken over by static fields and the gas lens effect can be reduced. In effect this means a considerable reduction in gas pressure (to the order of one-tenth) needed for focusing, and greatly reduces the disadvantages which accrue from gas-filling.

(B) PRACTICAL FOCUSING ARRANGEMENTS. In dealing with focusing arrangements it is essential to decide whether magnetic or electrostatic methods should be used. Magnetic methods have the disadvantage of considerable current consumption if permanent magnets are excluded. Furthermore, they are expensive to produce. If for considerations of vacuum technique they are fitted outside the neck of the tube, an extended field, i.e. a thick lens, is unavoidable. Electrostatic optical systems are much better. Here only a potential, instead of a current, is required, and is easily supplied by connexion to the usual supply apparatus. Also the attachment is simple and easily fitted inside the tube. In some forms of construction, particularly those electrode systems developed from cylinders, they are very little affected by stray external fields. The walls of the cylinder at the same time act as screens. This is very important since very compact assemblies supported on a single glass pinch become possible. The facts mentioned may suffice to show that in the modern high vacuum sealed-off tube electrostatic electron-optical systems are almost exclusively used. The process for improving the efficiency of the tube, i.e. preliminary focusing for high vacuum and gas-filled tubes,

* M. von Ardenne, *Beiträge zur Elektronenoptik Braunscher Rohren*, l.c. page 251.

shows certain similarities, as even in the first years of development of the gas-filled tube an electrostatic optical system, though only a simple one, was used for pre-focusing.

(i) PRELIMINARY FOCUSING. (*a*) *Focusing by Electron Optical Electrode Systems.* The preliminary focusing arrangements may first of all be applied to the cathode itself. Forming a beam by shaping the cathode surface has been shown to be unsuccessful. In ion tubes, the cross-section of the cathode drop area, in front of the cathode surface, is small compared

FIG. 12. POINT SOURCE OF EMISSION AND ANODE APERTURE

with the dimensions of the cathode and not affected therefore by its shape. In hot cathode tubes the space charge cloud developed in front of the cathode determines the field structure in the cathode drop area, and can only be influenced in a very small way by the shape of the cathode.

Fig. 12 is a photograph of a point source cathode and an anode gun during operation. The hot cathode, as can be seen, emits practically as a point-source. Under the influence of the space charge, a broad cone of rays has been produced, and from this a narrow central stream has been formed by the anode. The efficiency is barely 10 per cent.

Fig. 13 explains diagrammatically an important electrostatic method for preventing the divergence of the rays shown in Fig. 12, and this is especially suitable for hot cathodes. A negatively charged Wehnelt[17] cylinder surrounds the emitting

point-source cathode concentrically. The anode is mounted concentrically in front of the cathode assembly, and can take the form of a perforated screen, wire ring, grid, or an arrangement of similar construction.

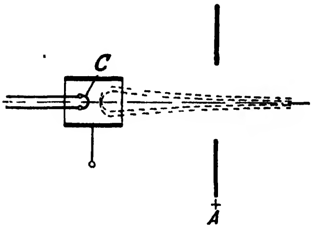


FIG. 13. ACTION OF THE WEHNELT CYLINDER

When placed in a suitable position and biased to the requisite voltage, the cylinder modifies the field between the anode and cathode in such a way that the divergent lines are compressed. The cathode rays can no longer reach the walls of the cylinder, and must leave the interior of the cylinder at a diverging angle, which decreases in magnitude as the value of the negative voltage is increased.

Fig. 14 was taken in the same way as Fig. 12, with a gas-filled hot-cathode tube and a Wehnelt cylinder. To simplify observation the cylinder was cut open as shown. The bias voltage is

FIG. 14. ELECTROSTATIC FOCUSING WITH LOW BIAS VOLTAGE

still comparatively low and the stream of rays is so compressed that the total beam can just pass through the small opening to the anode gun. In the sketch, the cathode dark space which is about 1 to 1·5 mm. long, is clearly visible, and shows up the path in which the electrons have not yet reached their ionizing velocity.

In view of the use of such tubes for television it does not appear expedient in the case of high-vacuum tubes to reproduce

an image of the cathode surface directly on the fluorescent screen, which was almost the general practice with the old type of tube. Pre-focusing or brightness control can be carried out successfully in a particularly simple and accurate manner with such arrangements, where an intermediate image or a surface of small area and high electron density is reproduced, similarly to the high voltage oscillographs by Rogowski and Flegler.* Such an arrangement has been published by George, H.,† and is reproduced here in Fig. 15. An electrostatic accelerating lens with cylindrical electrodes (4) and (5) serves as the main portion of the optical system. A very small cross-section of the ray which is projected through the fine hole in the disc is used for forming the image. Preliminary focusing is effected by a system of short focal length, opposite the main system, the electrode (2), which has a small negative bias, acting as a Wehnelt cylinder. The cathode (1) is of the plane type. Various possibilities accrue from Figs. 16 and 17, where small diverging angles can be secured with the greatest possible area of cathode emission surface. These, however, result in greater cross-sections of the ray at the point where the image is formed. Simple experimental trials with systems similar to that of Fig. 19 confirm this.

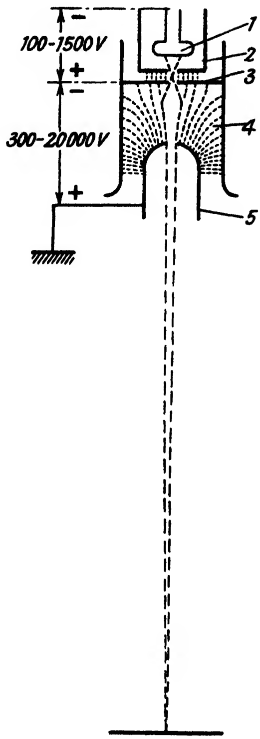


FIG. 15. ARRANGEMENT WITH DUAL ELECTROSTATIC FOCUSING (*George*)

It is possible to estimate directly the cross-section of the ray by side observation at the disc which is covered with calcium tungstate, if the ray is deflected slightly from the centre by a magnet. In general, separate investigation and co-ordination of the various parts of the system has proved very successful during the course of development.

* W. Rogowski, and E. Flegler, British Pat. No. 295, 710.

† R. H. George: "A new type of hot cathode oscillograph and its application to the automatic recording of lighting and switching surges." *J.A.I.E.E.* 48 (1929), 534.

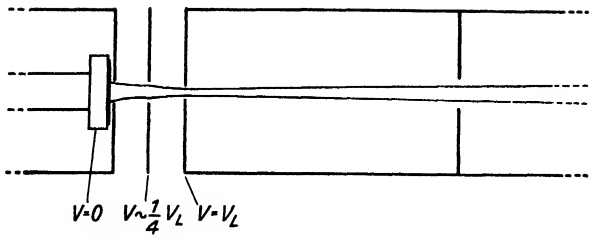
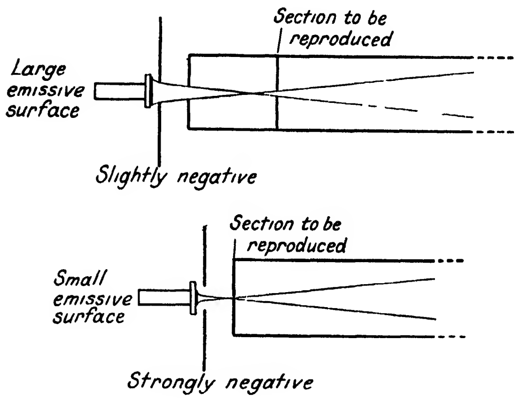


FIG. 16. REDUCTION OF THE ANGLE OF DIVERGENCE BY EXTRA ACCELERATION



FIGS. 17 AND 18 COMPARISON OF DIFFERENT SYSTEMS OF PRE-FOCUSING FOR EQUAL DIVERGENCE OF THE CURRENT BEAM

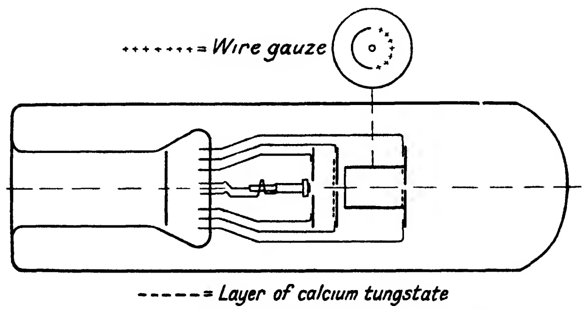


FIG. 19. SPATIAL DIVERGENCE OF THE PRIMARY EMISSION BEAM

Important facts about the design of a complete system can be deduced if we consider at first the case where only one point of the cathode is assumed to be emitting, and look at the smallest section of which the main optical system forms an image under such conditions (the case when high negative bias exists). The diameter of the image is then

$$d = 4a_1\sqrt{V_{maxw}/V_L} \quad . \quad . \quad . \quad (7)$$

where a_1 is the distance between the intermediate image and the cathode, V_{maxw} is the mean emission velocity of the

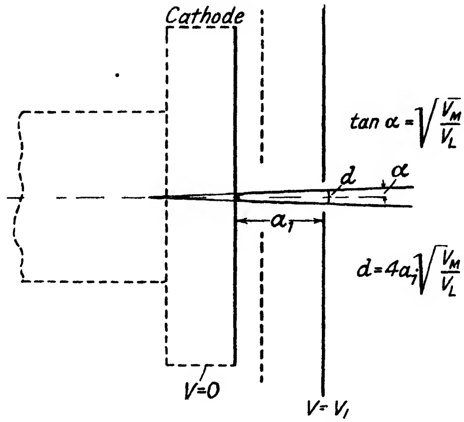


FIG. 20. ANGLE OF DIVERGENCE OF THE ELECTRON BEAM NEAR THE CATHODE.

electrons in volts at the existing cathode temperature, and V_l the voltage of the accelerating electrode.

In deducing this formula, the field between the cathode and the accelerating electrode is regarded as uniform, which assumption is justifiable as long as the aperture of the disc is small compared with the distance a_1 in Fig. 20. Furthermore, the equation of motion was selected for the most unfavourable case of the direction of the initial velocity at the plane of the cathode. By combining this formula with equation (4) given above for the magnification of a system with an accelerating lens, the smallest diameter d_s of the fluorescent spot follows from the relation

$$d_{s\ min} = 4a_1(b/a)\sqrt{(V_{maxw}/V_a)} \quad . \quad . \quad (8)$$

The equation proves that in the system investigated and under conditions where the intensity control is at "dark," the sharpness of the fluorescent spot only depends on a few factors. A small value of a_1, of image distance, large distance of object, low emission temperatures, and high anode voltages are favourable to sharpness of the spot. According to experimental evidence, the equation seems to be applicable to emissive surfaces, the diameters of which are small compared with a_1. The diameter d_s always increases by a certain factor corresponding to the diameter of greater emission. Having considered the factors which determine the diameter of the spot, we will now consider the ray current.

The angle of divergence β, which is formed by the beam when considering the intermediate image as a source of electrons, plays an important role here. The greater this angle, the greater may be the portion of the cathode surface contributing to the ray current at a constant value of V_l/a_1. For ray current I_a at not too great emissive sections is given by

$$I_a = K \cdot \tan^2\beta \quad . \quad . \quad . \quad . \quad (9)$$

approximately, where K represents the effect of the remaining factors. With constant magnification of the main system $\tan \beta$ is proportional to $\tan \gamma$.

The converging angle 2γ determines the cross-section of the electron beam at the point where deflection takes place as well as the effective cross-section of the electron-optical system which is not generally materially different. This shows that the control of large convergent angles γ in the deflection space is of considerable importance in the design of a system producing cathode rays. For a given angle of convergence, β can only be increased by decreasing the distance of the object, i.e. increasing the magnification. A compromise between the sharpness and the brightness of the spot must therefore be made during construction.

In the system described above, the area of the emitting cathode depends on the bias v_g of the brightness control grid or pre-focusing electrode chosen. If the diameter of the heated oxide surface becomes larger than the diameter of the aperture in the control electrode, the small negative bias at which the angle of divergence discussed can just be filled, can in practice be found easily. Now how is it possible to ensure that while this angle is filled, the anode current is as high as possible?

In view of the extremely low penetrance*[18] of the main anode (low value of D) the known equation

$$I_a = K(V_g + D \cdot V_L)^{\frac{3}{2}} \quad . \quad . \quad (10)$$

applies for the anode current. The emission constants, the effective mean distance between the control electrode (grid) and the emissive surface and the size of the effective emissive surface are included in the magnitude K. The penetrance (1/amplification factor) depends on the aperture in the control electrode, its distance from the cathode and the distance a_1. A complete answer to this question seems very difficult on account of the many and mathematically obscure relations between the various components of the preliminary focusing system. According to the collected experimental evidence, small values of the distance a_1 appear to be favourable to the production of high anode currents, but a limit is set by the increase of the specific emission of the cathode (Knoll)[18] surface which becomes smaller as a_1 decreases and which in view of its life must not exceed 0·1 mA./mm.^{2} An improvement can be made here by using a cathode of higher oxide content.

Preliminary focusing by magnetic fields is a method frequently used with high voltage oscillographs (Rogowski).† It is particularly useful for tubes of this type since it permits of external mounting which avoids the structural difficulties and insulation troubles associated with electrostatic control.

The disadvantage of the extra load is not of much importance in such large equipment. On the other hand, electrostatic control is much to be preferred for low voltage oscillographs, as its excitation imposes no load on the circuit.

(*b*) *Gas-focusing*. The concentration of the rays due to the presence of gas already mentioned is the simplest in arrangement and operation. The inclusion of slight traces of gas at pressures of 10^{-3} to 10^{-2} mm. into the tube results in the formation of an electron jet when a certain current density has been reached and the whole of this passes through the anode gun.

(*c*) *Composite Focusing Arrangements*. Composite focusing

* The term "Durchgriff," is rendered by the English word *penetrance*, which appears to be the nearest if an inadequate equivalent. It is the reciprocal of the amplification factor expressed as a percentage, and is denoted hereafter in symbolic notation by the letter D.

† W. Rogowski. But Pat. 295,710.

devices consisting of electrostatic or magnetic and gas lenses as distinct from the arrangements discussed in the two previous sections, only differ quantitatively and not in principle from them.

(ii) Main Focusing in Deflection Space. (*a*) *Focusing by an Electron Optical System.* If a good preliminary concentration of rays has been secured, there will be an intense homogeneous beam of rays, uniform in direction and having relatively low diffusion, at the entrance to the deflection chamber. Little difficulty is experienced in high voltage tubes in keeping the beam of rays in its path right up to the screen, for the following reasons. First, very little diffusion can take place since at the high electron velocities in question, the effective disturbance due

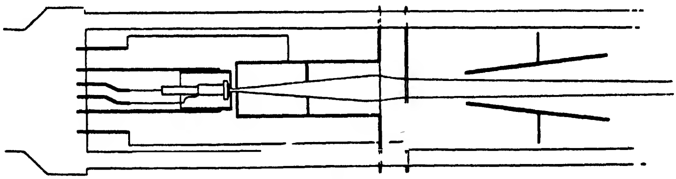


Fig. 21. System of a High-vacuum Television Tube by the Author
(*Leybold – v. Ardenne*)

to the remaining gas molecules is small and most of them are passed by without ionization. Furthermore, the internal field of the beam itself (internal space charge in the ray) becomes less effective owing to the high electron velocity. The relatively small divergence of the rays which remains can be compensated by focusing coils.

With lower anode voltages, particularly with low voltage oscillographs which operate at less than 10 kV., a sharp pencil of rays cannot be maintained over the whole length of the discharge space, in which there is no field, without special measures. Apart from the magnetic focusing coil, a special electron-optical system must be introduced in the high vacuum in order that an image of the cathode may be formed as a sharp fluorescent spot on the screen.

Fig. 21 gives a fair idea of the system developed by the author for producing rays in a high vacuum tube. The main difference as compared with the arrangement of Fig. 15 is the greater distance of the object resulting from choice of other electrode dimensions. For clearer understanding, the various

dimensions of importance of the system in question are given in Fig. 22.

Figs. 23 and 24 illustrate two systems of cathode-ray tubes

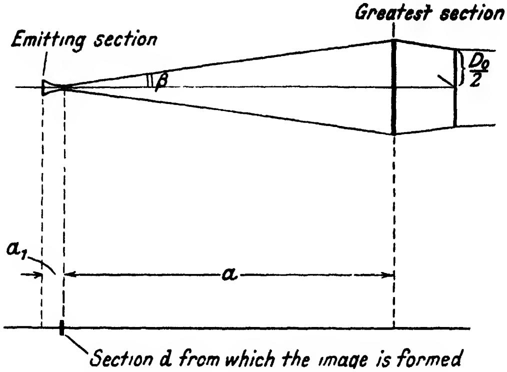


FIG. 22. DIMENSIONS OF THE RAY-PRODUCING SYSTEM

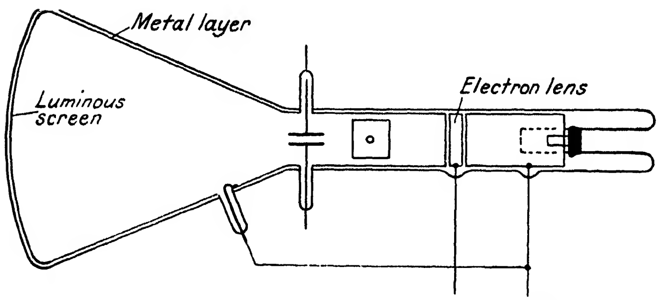


FIG. 23. HIGH-VACUUM TUBE WITH SINGLE LENS (*M. Knoll*)

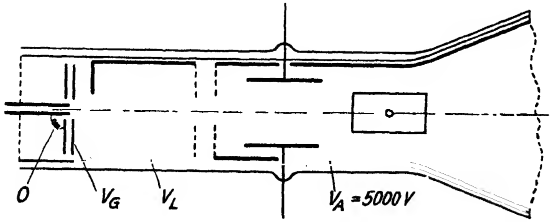


FIG. 24. TELEVISION TUBE WITH SIMPLE ACCELERATING LENS
(*Knoll, Knoblauch, and Diels*)

developed at the Telefunken works by Knoll,* Knoblauch, and Diels.[19] The principal electrical converging lens of the first system mentioned (Knoll) is a so-called *reversing lens*, the centre portion of which is at a negative potential with respect to the electrode on the cathode side. This lens, therefore, represents a combination of accelerating and retarding lenses. The simplicity of construction of the lens is noteworthy. The single lens is indicated in the internal metallizing, as the space between two rings.

The system in Fig. 24, developed by Knoll, Knoblauch, and Diels, has an accelerating lens as the main focusing unit.

The large aperture of the lens systems in both arrangements goes a long way to avoiding aperture errors. The path of the ray in the tube shown in Fig. 24 is practically identical with that in the high-vacuum tube of Zworykin,[20] and the tubes shown in Figs. 15 and 21. It can be seen that development has already resulted in a compact construction for the ray-producing system in high vacuum tubes.

(*b*) *Gas-focusing.* Here, again, a simple and relatively cheap method is to dispense with a high vacuum in the deflection space and fill it with an inert gas to a pressure of about 10^{-3} mm. mercury. In view of the importance which gas-focusing still possesses in the technique of cathode rays, especially for low voltage oscillographs, it seems appropriate to consider this phenomenon here in greater detail. The use of gas-focusing in the deflection space differs only from the same method of preliminary concentration in the greater length of ray path to be restricted.

A few phenomena which will help to explain the basic principles of gas-focusing, already discussed, are described below. What takes place here cannot be presumed from what has happened in the discharge space. The fact that the two are quite distinct can be shown by separating these spaces by a Lenard window.

At the entrance to the deflection chamber, suppose there is a beam of rays of high intensity and uniform in direction attained by some kind of preliminary focusing in the discharge space. The electron velocities are between 100–1 000 v. As the gas pressure is increased the phenomena illustrated in Fig. 25 are observed. In a high vacuum, such a slow cathode

* *Arch. f. Elektrotech*, 28.1.1934.

ray without electron-optical focusing would soon become diffused, so that no fluorescent spot would appear on the screen at all. But if the pressure is increased, the focusing effect of the positive charge begins to be apparent. The first phase of this effect of gas-focusing in Fig. 25 is to be seen at 10^{-3} mm. pressure. The ray is surrounded almost up to the screen by a

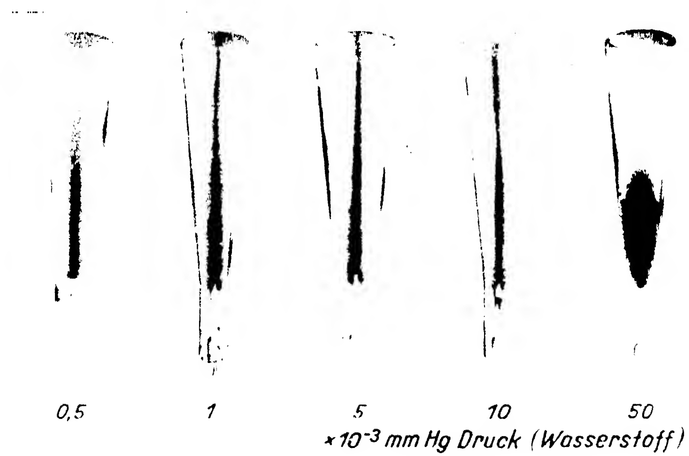


FIG. 25. FILAMENT-LIKE RAYS PRODUCED BY THE ADMISSION OF GAS INTO THE DEFLECTION SPACE (*W. Ende*)

misty luminous glow, and only at a pressure of about 5×10^{-3} mm. does a sharply defined stream of rays become visible. At the screen end a very small section of rays like a node has formed. By increasing the pressure still further, this node can be moved along the axis of the tube; as it approaches the narrow end of the tube a blur is again noticeable behind it, i.e. nearer the screen end of the tube. Obviously, the focusing effect of the gas is now so great that not only are the electron paths parallel through the focusing field but they are also converged to a spot.

This convergence becomes greater with increased pressure, i.e. with more intense ionization and therefore stronger focusing space charge, so that the node continually approaches the narrower end of the tube. With suitable geometrical arrangement of the tube, the electrons, after traversing the first node, become united in a further node or nodes. If the pressure

is too high, the ray is completely diffused and even at low voltages does not reach the screen (at 50×10^{-3} mm. Hg. in Fig. 25).

In Fig. 25 hydrogen filling was used, but the phenomenon described occurs in general with other gases. In Fig. 26, for instance, argon gas was used.

It is interesting to find out to what length an electron beam can be maintained with uniform cross-section and the magnitude of the section. As long as the accelerating voltages are not too low, e.g. not less than 300 volts, there is no difficulty in producing jets up to 1 metre in length. Brüche[21] and Ende

Fig. 26. Filament-like Rays in a Rare Gas
The node has been displaced to the centre of the path by too high a pressure
(*Photo by W. Ende*)

have produced such rays with a few hundred volts in their apparatus for measuring magnetic fields (electron ray compass). The gas does not appear to have much effect in retarding the ray along its path. It is not possible to end the jet in the middle of the gas space of short discharge tubes, except by using very low anode voltages—below 200 volts.

Spreading out in straight lines occurs in the space uninfluenced by any field, even in the case of the longest electron beams. As, however, the slow rays are very sensitive to the disturbing effect of stray fields, i.e. the earth's field, it is not very easy to employ them usefully for oscillograph streams of high sensitivity when more than 50 cm. in length.

As the cross-section of the jet is not constant over its whole length, adjustments must be made to bring the node to rest at the level of the screen. Many observations have proved that the jet does not consist only of a main stream of rays. A fairly

strong halo surrounds the spot in Fig. 27. Obviously, the screen, even at the greatest radial distance from the spot, is receiving

Fig. 27. Diffused Light Round the Focused Spot

impacts and is being excited, although much less intensely, by diffusing electrons.

When gas-focusing is used, a feeble secondary illumination of the screen takes place. The arrangement of the gun aperture has a limited influence on the intensity of this secondary

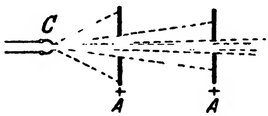


Fig. 28. Restricting the Rays by Diaphragms

illumination. It is rather less pronounced with very small apertures. The same effect can be produced when two discs with slightly larger apertures, instead of a single small aperture, are placed behind one another as shown in Fig. 28.

The halo is intensified by reason of an optical effect discussed below (see page 141, para (v)). That this is not the only cause, however, is shown by Fig. 29 illustrating an experiment[22] which explains the cause of the secondary illumination (due to diffuse radiation). By holding a magnet in front of the screen, the ray was induced to return to the interior of the tube by a path forming a loop. Not only the spot, but also the secondary illumination, disappeared and the diffused light was diverted at the point at which the field influenced the main

ray. It can be assumed, therefore, that the ray carries with it the diffusing electrons, that their paths do not differ greatly in direction from the main ray, and that their velocities are slightly less than the main stream.

Fig. 30 (Ende)[23] shows the influence of gas pressure on ionization. The effectiveness of gas-focusing is here shown not only by the magnitude of the mean cross-section of the rays, but in terms of the distance of the first node which is easily measured

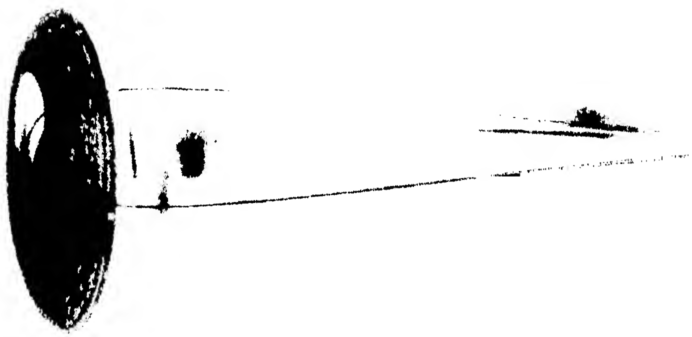


FIG. 29. SIMULTANEOUS DEFLECTION OF THE DIFFUSING ELECTRONS AND THE CATHODE RAY BY A MAGNETIC FIELD

and which becomes smaller the more the mutual repulsion has been compensated by the focusing effect. The measurements given clearly show a well-defined minimum gas pressure at about 3×10^{-3} mm. below which concentration of the ray paths is no longer possible. With gases other than hydrogen—the rarer gases whose effective section is less—these minimum values are smaller. The optimum point is not well defined and the pressure with hydrogen can be increased to about 10^{-2} mm. before a blur appears.

At low voltages the pressure limits are approximately inversely proportional to the voltage.

When the gas pressure is too low, in which case few ions are formed, improved focusing occurs when the ray current is increased, other electron optical conditions being the same. The curves of Fig. 31 confirm this relation; they show that above a certain current of about 1 mA.—which incidentally depends greatly on initial conditions (i.e. current density and

cross-section of the beam)—there is a gradual increase in focusing due to the increasing current.

The way in which the ionizing power of the electrons depends on the voltage was demonstrated experimentally by Kossel,[(24)]

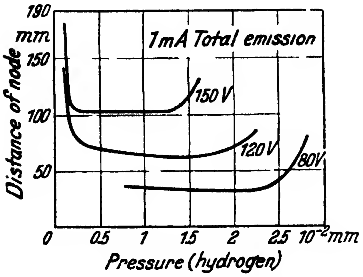


FIG. 30. RELATION BETWEEN GAS-FOCUSING AND PRESSURE (*Ende*)

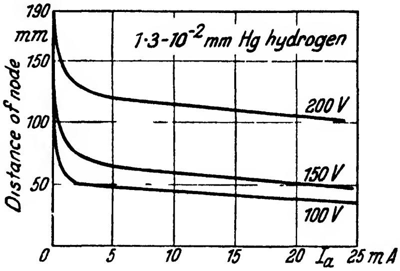


FIG. 31. GAS-FOCUSING AND CURRENT (*Ende*)

Compton,[25] and Wilson[(26)] for air up to voltages of 1 000; and for higher voltages in air, hydrogen, argon, and CO_2 by Buchmann.[(27)] Fig. 32 shows that at about 350 electron volts

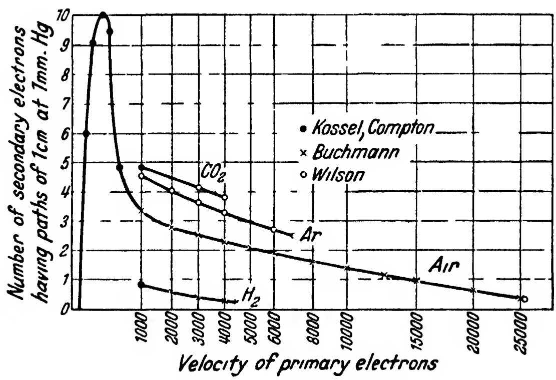


FIG. 32. RELATION BETWEEN ELECTRON VELOCITIES AND THEIR ABILITY TO PRODUCE IONIZATION (*Buchmann*)

the optimum condition is obtained for air. At very high primary velocities, the ionizing power is reduced since the atomic structure is then traversed without disturbance.

Curves showing the effective cross-sections of the atomic structures of various gases and the way in which they depend on the primary velocity in the low voltage range, are shown

in Fig. 33. These curves also show that there are points at which ability to produce ions by collision when the rays pass through the gases is a maximum.

Experimental investigations by the author have proved that gas-focusing, up to electron velocities of 7 000 volts, at increased gas pressures can be maintained, and that with hydrogen the highest ray velocities can be employed. Suitable pressures

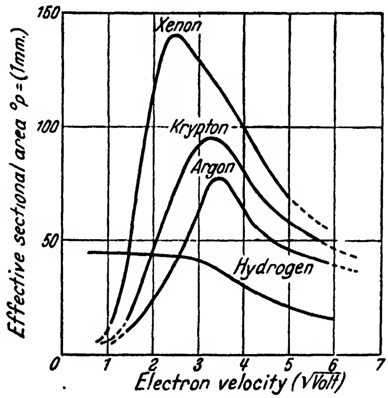


FIG. 33. MAXIMUM EFFECTIVE AREA OF GAS MOLECULES FOR SLOW-MOVING CATHODE RAYS

were of the order of 10^{-2} mm. With heavier gases the focusing became less at lower velocities, e.g. in the case of argon at just over 4 000 volts.

(c) *Composite Focusing Arrangements.* The principles stated for preliminary focusing with composite methods apply also in the case of the combination of electrical lens and reduced pressure gas-filling. The only difference is that here the "gas lens" has to perform the greater part of the refraction.

(iii) THE INFLUENCE OF THE SPACE CHARGE ON THE SPOT SIZE IN HIGH VACUUM. It has been pointed out in the preceding sections that, in a high vacuum, a bright and sharp fluorescent spot can only be secured as a small image of a real or virtual source of electrons, by means of an electron-optical system. If an ideal point source of electrons or one fixed at infinity and a perfect and accurately adjusted electron-optical system is assumed, the fluorescent spot would be formed at the focus of the beam of electrons converging from the optical system. Even if the above conditions are fulfilled, an ideal

point as a fluorescent spot must not be expected in view of the electron space charge in the neighbourhood of the focus of the electron beam, as this causes a very important limitation to the smallest possible cross-section.

Other conditions being equal, the greater the ray current the greater will be the smallest possible cross-section of the fluorescent spot, on account of the greater space charge. This condition is shown diagrammatically in the drawing (Fig. 31). An insurmountable limitation is set by the effect of the space charge in the construction of high vacuum tubes. The exact knowledge of this limitation with respect to applied anode

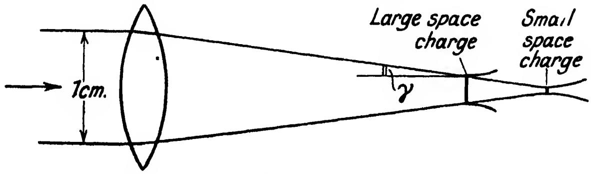


FIG. 34. LIMITATION OF THE MINIMUM SECTION OF A CONVERGENT BEAM BY THE SPACE CHARGE

voltage, ray current and magnitude of the angle of convergence, or for a given image distance, the value of the initial diameter, is of great importance, since it determines the possible peak output of the high vacuum tube. The results of an investigation of the space charge[28] effect in the deflection space are therefore given in rather more detail.

In carrying out the investigation, the same method of calculation was employed as that given by Zworykin.[29] The size of the limiting angle of the electron beam plays an important part, and is designated hereafter as the angle of convergence. This angle is 2γ (see Fig. 34). Special attention has been given in the investigation of the effect of space charge to the calculation of those curves which show the way in which the size of the spot varies with the angle of convergence or initial cross-section, and on the ray current for values of anode voltage most frequently used in television reception and for making measurements. The calculation is based on the assumption, which makes for simplicity, that the minimum spot diameter is always small compared with the initial cross-section, and further, that the function of the electron-optical system in collecting rays may be replaced by a corresponding initial radial velocity. This initial velocity is a result of the

radial acceleration component of the electron-optical system corresponding to the focusing voltage V_r of Fig. 35. The focusing voltage is calculated by the aid of a simple geometrical consideration in accordance with Fig. 35, thus—

$$V_r = (D_0^2/4b^2) \times V \quad . \quad . \quad . \quad (11)$$

where D_0 is the initial diameter of the ray, V the velocity of the electrons in volts, and b the distance of the image. The value of V_r is, therefore, for given angles of convergence linear with the anode voltage.

The space charge in the ray opposes the focusing voltage. The smallest diameter D_m is calculated from the formula

$$\ln D_0/D_m = (v_r^2 v/4ic) \times (m/e) \quad . \quad . \quad (12)$$

where v_r is the radial velocity in cm./sec. due to the focusing

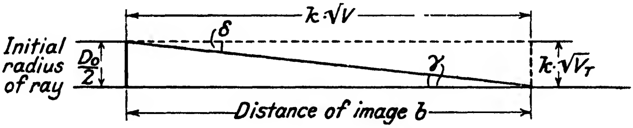
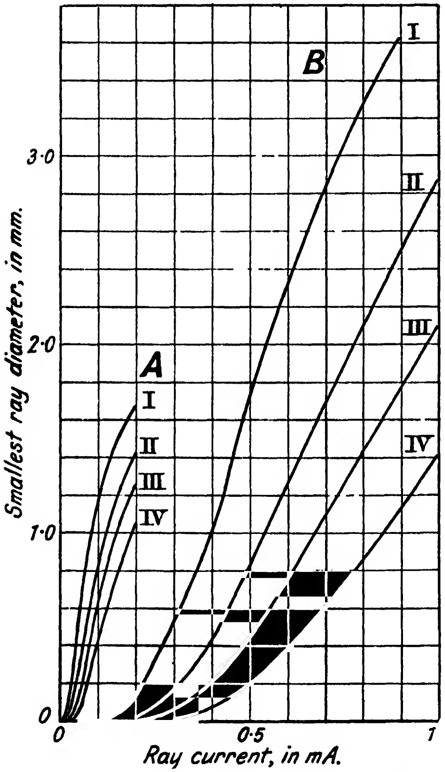


FIG. 35. DETERMINATION OF THE FOCUSING VOLTAGE FROM THE TUBE DATA (FOR RAYS NEAR THE AXIS)

voltage V_r, v the velocity in cm./sec. produced by the anode voltage V, i the ray current in e.m. units, c the velocity of light in cm./sec., (e/m) the electron constant in e.m. units. Fig. 36 shows the way in which the smallest ray diameter depends on the ray current for various anode voltages, taken for two values of initial diameter and focusing voltage. For simplicity the focusing voltage has been chosen the same for all anode voltages in each family A and B of the curves, so that various distances of image result. The corresponding angles of convergence can be calculated direct from the geometrical data and vary from 20′ to 1°. It will be seen that even under the most favourable conditions of large initial cross-section (curve B) and with anode voltages of several thousand, the highest permissible ray current is 0·5 mA. if the spot diameter is to be less than 1 mm. With the same anode voltages and an initial diameter of 0·25 cm., which frequently occurs in practice, the ray current to fulfil the same conditions must not exceed 0·1 mA.

These figures show that the high-vacuum tube is inferior,

in light intensity of the spot, to the type in which gas-filling compensates for the space charge, since with the same values of anode voltage and a spot diameter of 1 mm., the gas-filled tube at times permits of a current up to 1 mA. At the same time, however, a portion of this current will be conducted away



Initial Diameter
A = 0·25 *cm*
B = 1·0 *cm*

Curve		*Image Distance in cm.*	*Anode Potential in volts*
A	I	14·42	1 000
	II	20·41	2 000
	III	25·00	3 000
	IV	32·27	5 000
B	I	17·15	1 000
	II	24·14	2 000
	III	29·70	3 000
	IV	38·35	5 000

FIG. 36. MINIMUM RAY DIAMETER AS A FUNCTION OF THE RAY CURRENT FOR VARIOUS RAY VELOCITIES AND INITIAL DIAMETERS

by diffusion. It can be seen from Fig. 36 that with a certain spot diameter the greater the ray currents, the greater is the initial diameter or angle of convergence and the greater the anode voltage employed.

Of course, it is possible when fixing ideas for design, to view the matter from a different standpoint to that previously adopted. For instance, the anode voltage, the distance of the

image and the smallest spot diameter can be fixed and the question then asked: What initial diameter will give a certain ray current and therefore a certain output and spot brightness? The curves of Fig. 37 were calculated this way. If the condition of an infinitely remote or point source of emission is abandoned it is known that even without considering the influence of the space charge there is a certain minimum cross-section which depends on the conditions of the electron-optical system existing at the time. If the design of the whole system is such

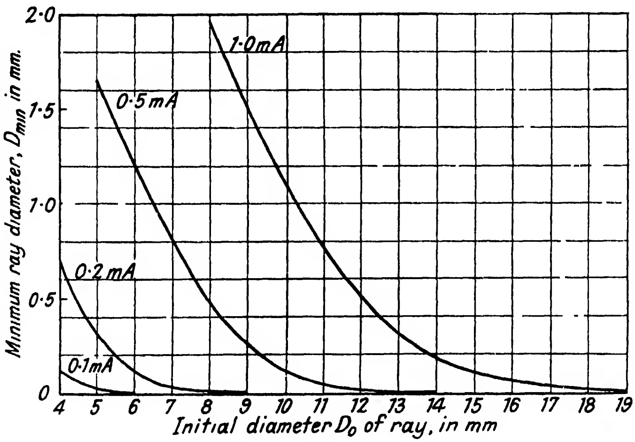


FIG. 37. MINIMUM RAY DIAMETER AS A FUNCTION OF THE INITIAL DIAMETER FOR VARIOUS RAY CURRENTS

that this minimum section is just equal to the smallest section determined by the space charge for the highest ray current under load, then under such conditions the size of the spot does not depend on the ray current, a characteristic which would be detrimental to the image, for instance, in television. Above all, efforts must be made, when designing the system which is the source of the rays, to ensure that as far as the electron-optical system permits, the ray current which reaches the deflection space can be easily controlled. For more detailed consideration, the effect of the space charge on the ray source would also have to be examined. The increase in size of the section of the intermediate image in particular, as well as the increase in the angle of divergence, must be investigated. A rough calculation for the ray currents limited by the conditions

in the deflecting space and the lens voltage existing in practice showed that the increase in size of the angle of divergence can generally be ignored.

The calculation was made by Watson[30] and Knoll and Ruska.[31] The enlargement of the intermediate image by reason of the space charge does not appear to affect the spot very much, since the more divergent angle counterbalances the lower electron velocity in this part of the tube.

3. **Current Path in the Tube.** A knowledge of the path taken by the current inside a cathode-ray tube is important if the operation is to be completely understood. The path taken

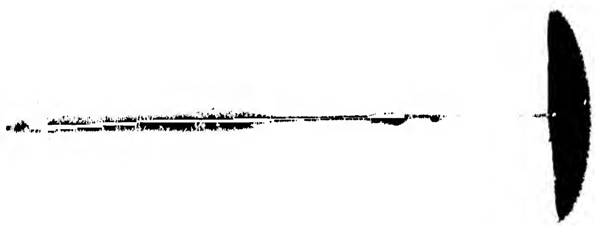


FIG. 38. INTERNAL LUMINOSITY IN AN OLD TYPE OF GAS-FILLED CATHODE-RAY TUBE

by the current in gas-filled electron tubes is made particularly distinct by the luminous phenomena which are produced. When a gas-filled tube operates, the luminous phenomena of Fig. 38 can be observed. The beam is clearly shown as a streak of light. It extends in a straight line up to the screen, where it terminates in a more or less distinct halo. The greater part of the bulb remains dark but in the region of the anode, a blur appears and increases in length as the gas pressure is reduced. In order to ascertain the course of the ray stream, the screen is metallized and a connecting lead taken to the outside of the bulb. An electrometer measures the voltage drop along the stream, between the anode and the screen and shows a value of 50 to 150 volts negative to the anode, i.e. less than 10 per cent of the anode voltage, which can be only slightly changed by alteration in current, voltage, and pressure. The path

between the anode and the screen is therefore shown to be one of very low resistance.

As soon as the screen is connected electrically to the anode, the whole anode illumination disappears momentarily and the whole of the interior of the bulb with the exception of the path of the stream remains dark. These experiments show that the course of the stream in ordinary tubes whose fluorescent screen is not connected to the exterior of the bulb can be assumed to be as follows. The secondary electrons produced at the insulated screen move under the influence of the low potential fall at the anode, in the vicinity of which they generate the luminous glow by collision with free ions. Inside the bulb between the screen and the anode there is an irregular diffused back stream which surrounds the electron jet on all sides. Figs. 39 and 40 show two experiments concerning this. The luminous space behind the anode has been influenced by either an electrical or magnetic field. The ray has been deflected in the same direction in both cases by this transverse field, i.e. upwards as shown in the illustrations. In Fig. 39 not only the ray but the whole luminous glow has moved upwards simultaneously because the upper deflecting plate has been connected to a positive potential. The space charge is consequently negative. This experiment gives no clue as to the direction of the current.

In Fig. 40 a magnetic field perpendicular to the plane of the paper has been employed. It can be seen that the ray bends upwards, whereas the luminous space charge bends downwards and to a much greater extent. This proves that these are actually back-stream electrons which, moving away from the gas space with lower velocity, return to the anode. As this back-stream completely fills the cross-section, it obviously also passes through the space between the deflecting plates. It can modify the field round the ray and cause deviation from the theoretically estimated deflection curve. It should be remembered, however, that the elimination of the internal back-stream by an external shunt is in many cases desirable.

The current path in a high vacuum is the same, except that in this case the partial compensation of the screen charge by positive ions naturally does not occur. With the usual insulated screens, the dissipation of the screen charge only takes place by secondary emission from the screen. In a high vacuum, therefore, only fluorescent screens whose secondary

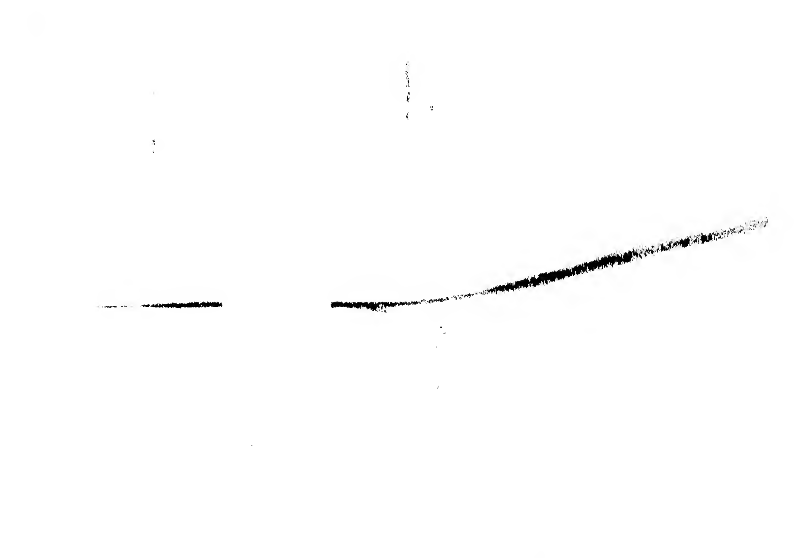


FIG. 39. ANODE LUMINOSITY IN THE ELECTRICAL FIELD

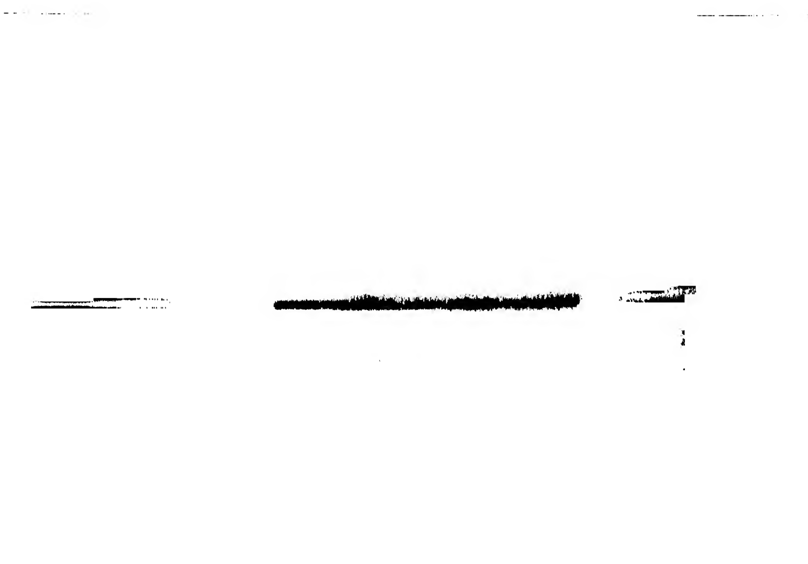


FIG. 40. ANODE LUMINOSITY IN THE MAGNETIC FIELD

emission factor is sufficiently large are used. In practice, it has been found that the ordinary screen materials nearly always provide a sufficiently high secondary emission. Even in high vacuum tubes the retardation of the electrons by the screen charge rarely exceeds 10 per cent of the anode voltage. The penetrance of the anode of the ray-producing system on the screen zone is sufficient to ensure that the return electron stream is quickly conducted away.

III. Control of the Energy of the Rays

1. **General Information concerning the Control of Energy of the Rays.** When the cathode-ray tube is normally used as an oscillograph every endeavour is made to use d.c. voltages which are as constant and free from interference as possible. The characteristics of the waves of alternating supply are liable to introduce fluctuations in sensitivity and may exercise an objectionable influence on the brightness of the spot and the curve it traces on the screen. Such modulation is, however, desirable in the case of some uses to which the tube is applied. When the energy of the rays is varied by a control voltage, there is the possibility of registering three instead of two independent variables, since the variation in brightness of the spot, as well as the co-ordinates of its position, are shown on the fluorescent screen. The best-known instance of this is the formation of televised pictures by the cathode-ray tube.

In other cases it is required to allow the ray to register its trace only during a certain space of time, and to cut it off before and after its working period. This happens in photographing single pulses of ultra-short duration; in which, from considerations of photographic recording, the inclusion of the spot at the end of its traverse is undesirable. In such cases the luminosity must be varied from full brilliancy to extinction by the brightness control.

If the modulation of the light is accompanied at the same time by a change in sensitivity, movements of the ray in rhythm with its energy modulation, but in addition to those due to static deflection, will take place. In consequence, it is possible to obtain registration in co-ordinates other than Cartesian, e.g. Polar co-ordinates (see the following section).

There are a few instances of cathode-ray tubes being used as relays and performing the functions of amplifiers. In such

cases the rays fall upon a trap electrode which takes the place of the fluorescent screen. From the examples given it follows that the modulated ray must, generally speaking, fulfil one of the following conditions—either the speed of traverse must be constant while the energy is varied, or the speed must vary while the energy remains constant. The first condition is fulfilled when variation in brightness has to occur at certain prescribed points on the image. This condition implies that the magnitude of the luminosity must be independent of the co-ordinates of the position of the spot, or that no change in position of a deflected ray must take place when the energy is being controlled. In television this condition must be fulfilled to about 1 per cent. Both types of control will now be considered in greater detail.

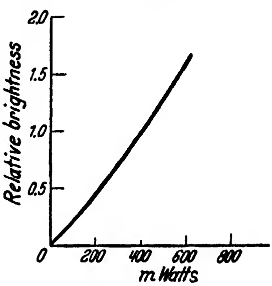


FIG. 41. RELATION BETWEEN SPOT BRIGHTNESS AND INTENSITY OF THE RAY

The brightness exhibited by the fluorescent material which will be influenced by energy control, depends only upon the energy. The result of a photometric measurement is given in Fig. 41, which shows the amount of light produced to the total amount of energy expended. The rays are composed of electrons having an elemental charge e of which n per sec. fall on the collecting electrode, e.g. the screen which has been raised to potential V. ne then is the charge transported per sec., i.e. the current. Then

$$N = n \,.\, e \,.\, V \quad . \quad . \quad . \quad . \quad . \quad (13)$$

is the energy absorbed by the collecting electrode. But according to the energy law

$$eV = \tfrac{1}{2}mv^2 \quad . \quad . \quad . \quad . \quad . \quad (14)$$

Moreover, with a density of q electrons per cm. of beam length, the number n transported per sec. is given by

$$n = qv \quad . \quad . \quad . \quad . \quad . \quad . \quad (15)$$

The output can also be written as

$$N = (\tfrac{1}{2}m)qv^3 \quad . \quad . \quad . \quad (16)$$

Therefore, the energy of the beam can be modulated by varying either q or v. The first would naturally be termed *current modulation* and the second *velocity modulation*. With current modulation it must be possible to keep the electron velocity v constant, whereas with velocity modulation it is a question of operating with constant current.

2. **Methods of Energy Control.** First of all, let us consider current modulation at constant velocity, which is the more important of the two modulation processes.

(A) CURRENT MODULATION. As the control of the number of electrons emitted per second is really a matter of adjusting the cathode output, the position of the control electrode is usually in the neighbourhood of the cathode, i.e. in the discharge space. The process is similar to that of which use is made in amplifying valves and can be caused to take place by means of cold control electrodes placed between cathode and anode. The control by means of the grid electrode must be distinguished particularly from that involving control by a diaphragm.

(i) *Grid Control.* The method of operation of this process of energy control depends on whether it is applied to high-vacuum or gas-filled tubes. In the former case the focusing effect depends merely on the geometrical disposition of the cathode, anode, and control electrode. If the tube contains gas to secure auxiliary space charge focusing, the control conditions become much more complicated. The control element in this case not only causes a change in the number of electrons reaching the screen per second, but also brings about, by reason of this change of cathode output, an alteration to the focusing effect of the space charge. The effect of the control on focusing is large or small according to the shape and position of the control electrode relative to the cathode dark space. The size of the cathode dark space is dependent on the geometrical arrangement of the control element.

A perfect control system must therefore result in focusing which is consistently good, and must have characteristics which are not liable to change. There must be no variation in diameter of the fluorescent spot over the whole modulation range of the control voltage which, if possible, should be large.

Below are discussed various methods of controlling the ray current which were employed in the course of development. Some of the arrangements referred to are not perfect, from the

electron-optical point of view. The latter methods have therefore given only fairly good results with gas-filled tubes since the effect of gas-focusing was stronger than the control by external electron-optical means. Following the trend of historical development, brightness control is discussed in turn as relating to the high gas-pressure tube, and that with reduced gas pressure as well as the high-vacuum tube.

The simplest form of current modulation, ignoring the very slow modulation due to the heater current which alters the focusing to a considerable extent, is the control by means of a grid in the path of the stream between the cathode and

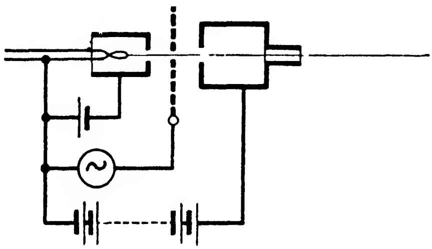


FIG. 42. CURRENT MODULATION BY MEANS OF A CONTROL GRID (*Skaupy*)

the anode.[32] The electrode arrangement is shown in Fig. 42. This geometrical system does not give very satisfactory operation with a gas-filled tube, and in consequence is seldom used. If the grid is fitted outside the dark space, as is nearly always the case in practice, then control of the rays by high-frequency sources is scarcely possible.

In the high-vacuum tube also this form of arrangement is not very suitable since the wires of the grid in the ray path cause considerable disturbance in the formation of the image.

Current modulation without a special type of control grid is shown in Fig. 43. A controlling a.c. voltage is superimposed on the d.c. potential of the Wehnelt cylinder.[33] This arrangement has attained very considerable importance for tubes with and without gas-filling.

Let us consider next the forms of construction and results of the old gas-filled type of tube.

The heated cathode produces a space charge cloud of electrons which surrounds the emission element and which represents the point of origin of the rays. In a construction without

negatively biased control element (Wehnelt cylinder), the number of electrons required for the production of the rays at constant gas pressure and anode voltage must be accurately adjusted by means of the emissivity of the cathode, i.e. the heating current.

The dark space between the cathode and the point where the rays may be considered to originate, which without any negatively charged control element is only about $\frac{1}{100}$ mm., is considerably enlarged when a negatively charged cylinder is employed. Hence, it can be proved that the potential gradient

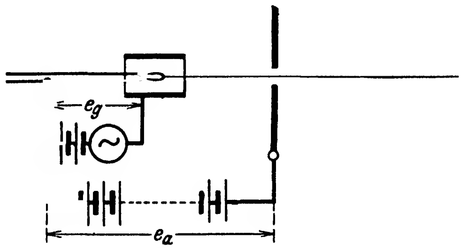


FIG. 43. CURRENT MODULATION BY WEHNELT CYLINDER

around the cathode is decreased, in other words, the strength of the field in the neighbourhood of the cathode is considerably reduced by the negative bias on the cylinder. With such a negatively charged cylinder only a small fraction of the electrons in the cloud and around the cathode contribute to the actual cathode ray. The variation of the number of electrons may be described pictorially by stating that the number of lines of force extending from the anode to the space charge varies as the potential of the cylinder is varied, subject to the condition that the emissivity of the cathode is greater than that required for the production of the ray stream.

In order that the space charge at the cathode may be maintained, the cylinder must be negatively biased with respect to the cathode. In practice the static charge of the Wehnelt cylinder and the amplitude of the varying control voltage should be so chosen that at no time should the beam become sufficiently defocused to prevent the whole of the stream passing through the hole in the disc. With positive control voltage a large number of the electrons would flow to the cylinder.

The relation between the Wehnelt cylinder and the space

charge focusing is apparent in Fig. 44 from the control characteristics whose parameter is the anode voltage V_a. In the lower portion of the diagram the characteristic of $V_a = 2\ 000\ V$

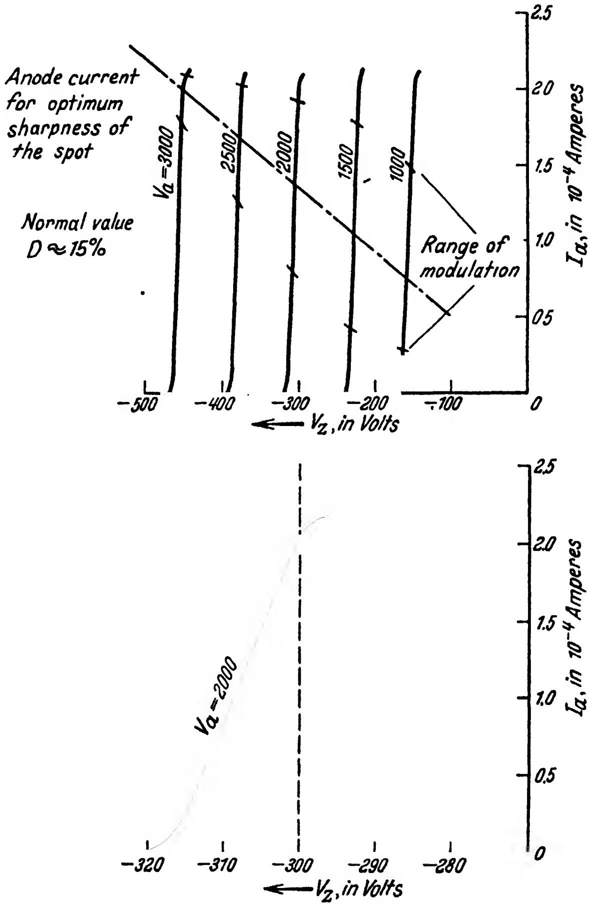


FIG. 44. CONTROL CHARACTERISTICS OF A GAS-FILLED TUBE IN WHICH THE BRIGHTNESS IS CONTROLLED BY A WEHNELT CYLINDER

is distinguished by greater abscissa measurements. This curve

$$I_a = f(V_z)_{V_a - \text{const.}} \qquad (17)$$

is linear over a wide range, so that the current when modulated will vary in proportion to V_2 over a considerable range of the

latter voltage. The calculated slope of such curves in high vacuum triode

$$s = (\delta I_a / \delta V_z)_{V_a \text{ const}} \quad . \quad . \quad (18)$$

shows that with constant heating and gas pressure it is independent of the anode voltage. From the outline of the characteristics, in gas-filled as well as high-vacuum tubes the value of D—which depends only on the dimensions of the electrodes—of the anode voltage V_a through the cylinder aperture of the cathode can be determined.

$$D = \delta V_z / \delta I_a = \text{const.} \quad . \quad . \quad (19)$$

The internal resistance of the discharge region is given by

$$R_i = (\delta V_a / \delta I_a)_{V_z \text{ const}} \quad . \quad . \quad (20)$$

All three values calculated in Fig. 44 with constant heating, electrode construction, and gas pressure, are connected by the Barkhausen formula

$$s \,.\, D \,.\, R_i = 1 \quad . \quad . \quad . \quad . \quad . \quad . \quad (21)$$

Since these relations apply also to high-vacuum tubes, it follows that in gas-filled tubes a controllable discharge is present.

In the kind of discharge dealt with here D is constant. The positive space charges do not appear to influence the electrical fields. Since the voltage governing the electron emission may be expressed by the relation

$$V_c = V_z + D \,.\, V_a \quad . \quad . \quad . \quad (22)$$

where D = penetrance (*durchgriff*), it follows that, other things being equal, the anode current I_a no longer appears as a function of anode and cylinder voltages, but will depend on the control voltage V_c and the emissivity of the cathode, the value of D being the same for different values of the heater current. The currents flowing to the Wehnelt cylinder are not troublesome when gas-filling is used. With negative bias they are less than 10^{-7} amperes; consequently, in spite of gas-focusing they are of the order of ·01 of the anode current. Although, as can be realized from the direction of the current, positive ions are the carriers of the control cylinder current, their presence has practically no influence on the course of the field in the Wehnelt cylinder. The positive space charge required for gas-focusing

remains almost wholly confined to the central path of the ray, so that the configuration of the lines of force remains unchanged.

Furthermore, the end of the control range for each anode voltage has been sketched on the control characteristics shown in Fig. 44. Inside these no diminution of focused spot takes place. The control range corresponds to higher anode currents as the anode voltage is increased and at the same time becomes smaller.

This is explained by the fact that the number of surplus ions available for producing the focusing effect becomes smaller as the anode voltage is increased, i.e. as the electron velocity is increased due to the decreased probability of ionization. An

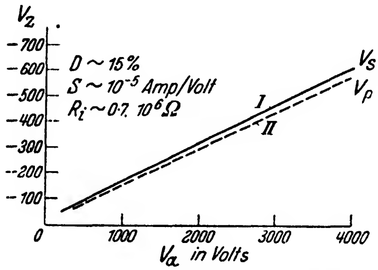


FIG. 45. CHARACTERISTIC FOR COMMENCING RAY CURRENT (I) AND OPTIMUM SPOT ACUITY (II)

increase in the negative voltage applied to the Wehnelt cylinder beyond the limit of the control range will result in an insufficient supply of positive ions for focusing.

Finally, with every characteristic in Fig. 44 the anode current, which naturally increases with increasing electron velocity, is shown for each case of optimum brightness of the spot. If modulation occurs, producing a variation between the extremes of complete darkness and optimum brightness of the spot on the screen, the ray stream will vary between the limits of zero and that value required to produce the optimum focusing. The range of the anode current will be confined by the limits V_s of the extinction voltage on the cylinder and the spot voltage V_p. The difference $V_s - V_p$ increases as shown by the curves in Fig. 45, showing the relation between the extinction and optimum spot voltage in relation to increasing anode voltage (Fig. 44). At a given gas pressure fewer positive ions available for focusing are produced per electron at high anode voltage.

In order, therefore, to secure the necessary balance between electrons and ions for the formation of the spot, a greater number of electrons must be emitted as the voltage increases. In short, this means that providing the focusing electrode is of suitable dimensions (see later), and that the geometrical axis of the cylinder coincides with the optical axis of the ray, precise modulation of the current without displacing the spot can be carried out by cylinder control over the useful range of spot brightness.

However, where high-frequency control voltages are employed anomalies arise in the current modulation by the Wehnelt cylinder. These phenomena, observed by the author during experiments, will be discussed by the aid of Fig. 46. When an

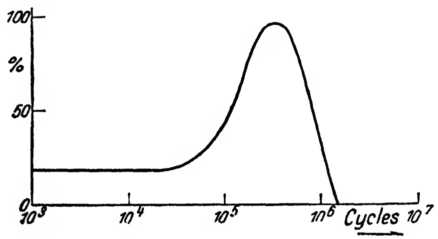


FIG. 46. CURRENT MODULATION BY WEHNELT CYLINDER (ARGON FILLING) AT HIGH FREQUENCIES

a.c. voltage of variable frequency but constant amplitude of $\pm 1 V$ is applied to the Wehnelt cylinder of a normal cathode-ray tube, it can be observed that in the frequency range up to about $5 \cdot 10^4$ cycles a luminous variation of about 20 per cent of the stationary effect occurs. Above the value mentioned the variation increases rapidly. In the case of tubes filled with argon the variation increases to 100 per cent at frequencies just over 10^5, and with the same modulation amplitude. Just beyond this frequency range the variation determined experimentally drops away very quickly. It is of particular interest that at frequencies over 10^6 cycles per sec. current modulation no longer occurs, obviously, in consequence of gas inertia. The discovery of this particular frequency limitation deserves special consideration when using this method of control in gas-filled tubes for television.

The errors of control by the Wehnelt cylinder just discussed are caused partly by gas-filling (the way in which the shape

of the spot and its sharpness depend on the ray current and the relation between load and frequency, etc.), and partly by the eccentric position of the point of emission in the tube system (changes in the position of the spot). Both types of error can be observed in the reduced pressure type of tube discussed above, though to a less extent. By fitting an electrostatic or electromagnetic converging lens between the cathode system and the fluorescent screen, the focusing due to the electrode system is improved so much that a very much weaker

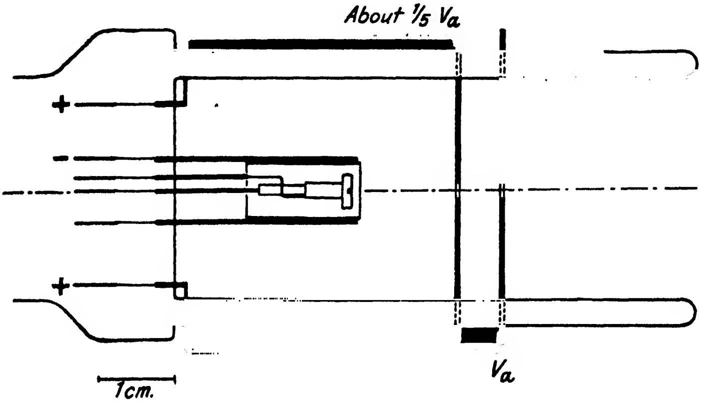


FIG. 47. ELECTRODE CONSTRUCTION OF A TUBE WITH WEHNELT CYLINDER AND ELECTROSTATIC ACCELERATING LENS AND REDUCED GAS PRESSURE

space charge is sufficient to bring about the focusing which is still necessary. In terms of electron optics, this means that the image of the cathode on the screen is formed, as before, by the help of an additional lens with smaller magnification. The illustration, Fig. 47, shows diagramatically, the electrode construction of a tube with Wehnelt cylinder and accelerating lens. Whereas with the older system with point cathode and simple anode, a magnification of approximately forty times the emission region was seen on the fluorescent screen, the magnification by the system described having an accelerating lens instead of a simple anode is only about 10–12 times. Although in this system the gas-filling could be reduced to one-tenth the gas pressure of the older system without discontinuity of the gas-focusing effect, the various errors in the brightness control are still so pronounced that reproduction

of fine-grained television pictures free from disturbances is not possible. Fig. 48 illustrates the relation between the error in change of position, which is frequently to be observed in gas-filled tubes, and the magnification. The division of the accelerating space by the first anode or lens electrode affects the position of the control characteristics in such a way that they are no longer in the region of strongly negative bias voltages as in the older systems with simple anode. In general, conditions are chosen and the resulting value of D is such that

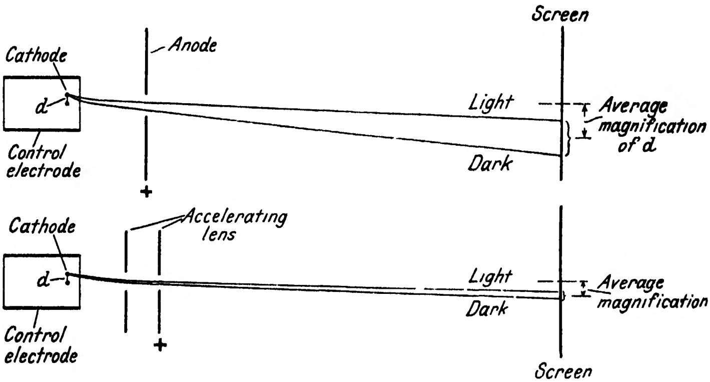


FIG. 48. RELATION BETWEEN THE ERROR IN THE BRIGHTNESS CONTROL AND SPOT ENLARGEMENT, FAULTY CENTRING OF CATHODE AND CATHODE IMAGE

the steep portion of the control characteristic is below 100 volts in the region of negative bias.

As the gas pressure is reduced, the neutralization of the space charge at the cathode is also reduced, so that by decreasing the distances and increasing the accelerating voltages and other factors, the potential drop in front of the cathode must be increased. In high-vacuum tubes, therefore, the electrodes carrying the accelerating potential are fairly close to the cathode. Nevertheless, in order to secure sufficient penetrance of the control field, i.e. to obtain a steep control characteristic, it is necessary to bring the control electrode very near to the cathode. In high-vacuum systems, which will now be discussed, the original cylinder shape has been replaced by flat control electrodes. Fig. 49 shows the arrangement of the brightness control electrode and the effect of various values of negative bias on the shape of the ray in a high-vacuum system. In this

system, which, as already mentioned, is employed in almost all modern high-vacuum television tubes, a small ray-section at the first accelerating electrode, which is provided with a narrow aperture, is reproduced on the screen. It can be seen at once that control of the illumination can hardly give rise to any change in position of the spot since the position of the ray-section reproduced is independent of the voltage of the control electrode. Only the size of the ray-section is altered as well as the angle of divergence at which the electron beam emerges

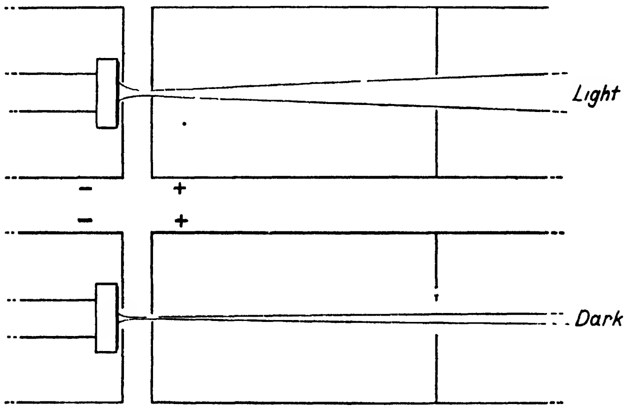


FIG. 49. EFFECT OF THE ILLUMINATION CONTROL ON THE SHAPE OF THE RAY IN A HIGH VACUUM

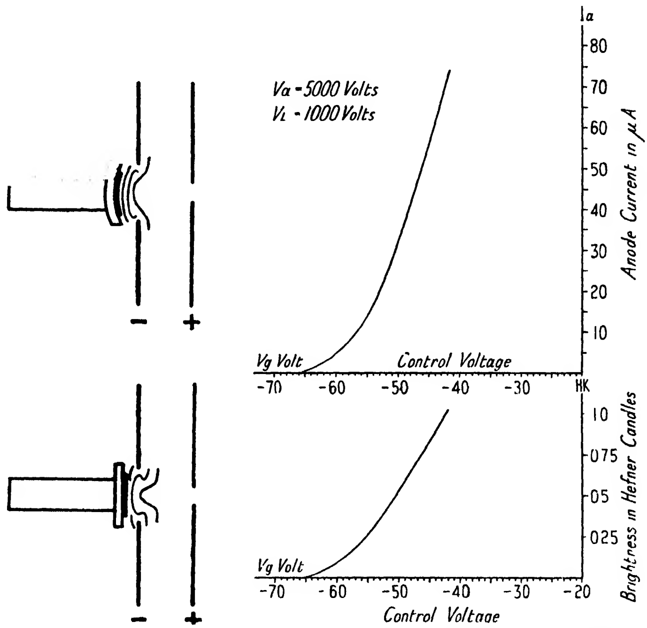
in field-free space from the aperture. The greater the bias the smaller the image of the cross-section of the cathode acting as the source of emission.

Greater uniformity in the oxide emissive surface, steeper slope of the control characteristic and therefore a high anode voltage can be secured if, by suitable form of cathode, and possibly also of the controlling electrodes, the emitting cross-section is prevented from fluctuating with variation of control as in the systems discussed previously, and that the applied field strength has the same value at all points of the cathode and undergoes the same change when the control is varied.

The purely diagrammatic drawing of Fig. 50 is a suggestion for approximating to this ideal.

The control characteristics of a high-vacuum tube show several notable differences as compared with those of a gas-filled tube given above. The characteristic of a modern high-vacuum

tube is shown in the curves of Fig. 51. The ordinate scale covers the range up to the point where the diameter of the spot assumes a value which is greater than that of a picture element in a 180-line picture covering the whole screen. The maximum sharpness of the spot exists, therefore, over the whole range of the characteristic indicated. As distinct from the gas-filled tube, sharpness of the spot is maintained down to the lowest values of anode current. In fact, as a result of the influence of



FIGS. 50 AND 51. TYPICAL CONTROL CHARACTERISTICS OF A MODERN HIGH-VACUUM TUBE

the space charge on the sharpness of the spot, it is as a rule even better with low than with high current values.

The magnitude of the maximum anode current is less than with gas-filled tubes. Nevertheless, the brilliancy of the spot is not much less than with the gas-filled type. In the high-vacuum tube there is no diffusion of electrons into the gas, and the whole of the ray current is effective at the fluorescent screen. In the illustration discussed, the measured light intensity characteristic is entered below the anode current

characteristic. Doubtless in the future the first characteristic will be considered of primary importance in television tubes. The increase in illumination due to the reduced effect of

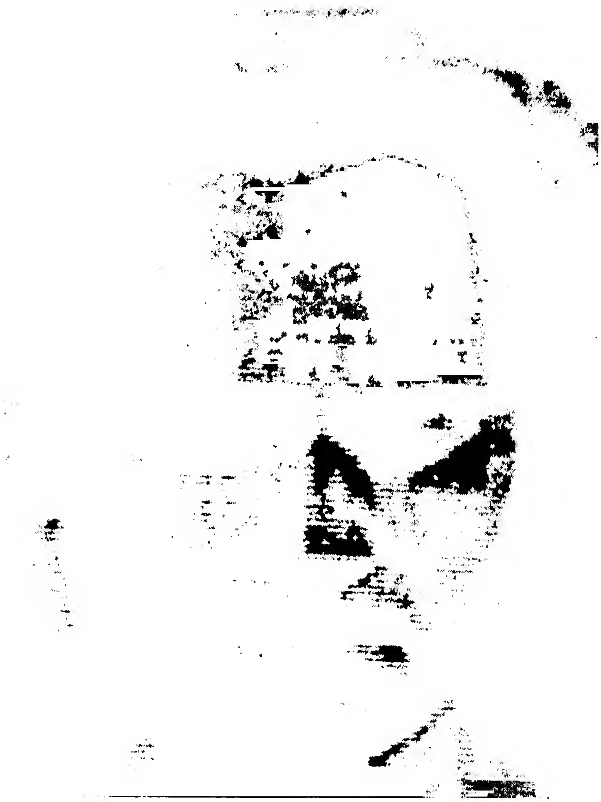


FIG 52 ENLARGED PORTION OF A TELEVISED SCREEN PICTURE

With black and white contrast to show that the position of the spot is independent of the ray current in the high vacuum tube characterized by the measurement of Fig 51

saturation when the ray energy is spread over a greater screen surface, is of particular importance in the measurements shown. The measurements on this high-vacuum tube show further that voltage changes of the order of 10 suffice for light-dark control of this system

That errors due to the brightness control do not appear

in a high-vacuum tube, is proved by the very much enlarged reproduction of a televised picture obtained by this system and illustrated in Fig. 52. It can be seen that the lines are quite straight even where light and dark parts overlap. The method of brightness control discussed is, to-day, as a result of its freedom from errors and its high sensitivity, nearly always used where these properties are essential. Nevertheless, for completeness, a few other methods are discussed in the next section, and these have frequently given good service in the course of development.

(ii) *Use of a Diaphragm.* In addition to the grid control there is also the diaphragm method of control. In this case, there is also a kind of cylinder control which we will discuss first. Its

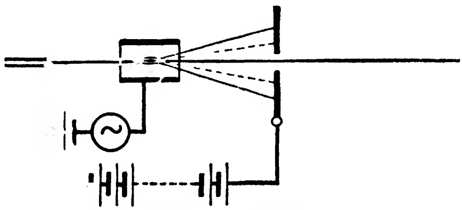


FIG. 53. CURRENT MODULATION BY MEANS OF DIAPHRAGM CONTROL

effect is explained by Fig. 53, and the photographic experiment shown in Figs. 54 (*a*) and (*b*). The method is based on the fact that with too low a negative bias on the cylinder, it is not possible to send all the electrons through the anode shield; a cone of rays is formed, only a fraction of which passes through the diaphragm. As the negative bias on the cylinder increases, the cone narrows and the efficiency and intensity of the stream increase in the deflection space, the ray velocity being unaltered. Two phases of this process are shown in Fig. 54 (*a*) depicting greater luminosity and narrower cone, and Fig. 54 (*b*) showing lower luminosity and a wide open cone. The modulation and mean luminosity obtained are poor. The large section of the beam behind the anode is another obvious disadvantage.

If diaphragm control is to be used it would appear best to keep the modulating voltage away from the focusing electrodes, and to apply only the constant voltage at which optimum focusing is obtained.

Fig. 55 shows an arrangement by which control of luminosity

(*a*)

(*b*)

FIG. 54. DIAPHRAGM CONTROL BY ALTERING THE FOCUSING

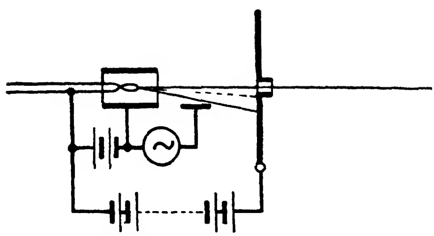


FIG. 55. DEFLECTED LIGHT CONTROL (*Claigh*)

can be effected. Here, the ray is drawn away from the shield obliquely by a special electrode. This has the advantage of enabling the whole beam to be steered, the diaphragm retaining its high sensitivity, and without the expenditure of energy. Behind the anode the beam is unaltered.

The arrangement is not perfect, however, in view of the deflection in front of the shield. The extent of this defect is less the smaller the diameter of the beam at the diaphragm. It can be reduced considerably by using a cylinder behind the anode disc, and charging it negatively with respect to the anode, forming with the latter an electron-optical system. A more satisfactory correction can be attained with the author's idea of using a counter-electrode behind the anode. This

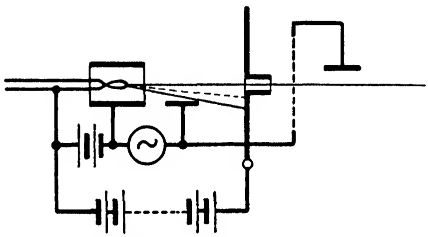


FIG. 56. DIAGRAM OF DEFLECTION CONTROL

arrangement of electrodes is shown in Fig. 56. By applying the same a.c. control voltage to each plate in front of and behind the anode, automatic compensation of the undesired deviation is accomplished. Even better results are obtainable —as practical experiments demonstrate—by connecting another cylinder between the compensating plate and the deflection plate assembly, and giving it a constant potential with respect to the anode. It follows as a matter of course in the unsymmetrical arrangement illustrated, that the electrodes controlling the illumination cause an alteration in the velocity of the electrons, but this is corrected by passing the electrons again through an electrode of constant potential. This objectionable velocity change can be avoided by using an electromagnetic instead of an electrostatic field for deflection of the rays. At the same time the magnetic deflection method is simpler, as the auxiliary electrodes for brightness control by connecting to a definite potential become unnecessary. In the older methods of stream modulation, the range of

control was not very great when good focusing was maintained. Very often two different methods of stream modulation are used in the tube simultaneously in order to obtain high modulation without sacrificing sharpness of the spot.

(B) VOLTAGE (VELOCITY) MODULATION. If the velocity of the electrons in a constant ray current is varied by a controlling field, voltage or velocity modulation occurs. Since the energy of the rays is proportional to the third power of the velocity, strong modulation is produced by very small alterations in the velocity.

The modulating electrode is seldom fixed near the cathode. Frequently, the anode of the ray-producing system, or in special cases a second anode near the screen, or even the screen itself, is used instead.

In the first instance electrons with modulated velocities are passed through the deflection space and, since the sensitivity to deflecting fields increases as the velocity decreases, radial expansion occurs on the screen. In this way, for example, a relation in polar co-ordinates can be portrayed (see below). Fig. 57 shows the effect of modulated anode voltage. The modulating voltage was an alternating voltage of radio frequency. By the aid of a synchronized time deflection (see below) a stationary figure of three modulation periods was produced on the screen. The modulated voltage had an amplitude such that the whole luminous scale was covered. The effect of the alteration in velocity on the deflectional sensitivity is indicated by the larger spot at the foot of Fig. 57. The lighter phases represent greater ray velocities, and therefore at their widest parts are directed towards the centre (top). The darker phases are directed outwards and the large spot displacement is proportional to the distance from the centre and is consequently zero at the middle of the screen.

FIG. 57. PHOTOGRAPH OF THE USUAL DISPLACEMENT OF THE SPOT WHICH OCCURS WHEN MODULATION IS CARRIED OUT BY VARYING THE ANODE VOLTAGE

(a) centre of screen
(b) spreading out of the ray

Displacement of the spot, which is troublesome in some problems, can be avoided by carrying out voltage modulation

after deflection, for instance, just in front of the screen. In the delayed acceleration process (Fig. 58) the ray passes through an extended network of thin wire which is at the same potential as the first anode just before it reaches the screen. The screen itself can act as the second anode and carry out the modulation. If the value of D through the network and the first anode is sufficiently small, the sensitivity of the tube will not be affected by what goes on at the screen. In carrying out voltage (velocity) modulation efforts should be made to ensure that the conditions under which the image is formed by the electron-optical system are not disturbed by the control operations. This condition must be satisfied when high-vacuum

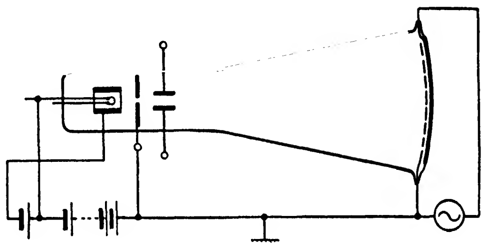


FIG. 58. CONTROL OF BRIGHTNESS BY VARIATION OF THE SUBSEQUENT ACCELERATION

tubes are employed. If the anode voltage in a high-vacuum tube is to be controlled, it is necessary, in order to maintain sharpness of the spot, that a portion of this control voltage should be tapped off to the lens forming the image, and that this should be of correct amplitude.

With modern high-vacuum tubes where an accelerating lens is provided, the necessary voltage required for it is taken from a voltage divider and the arrangement is free from errors if the total voltage across this divider is modulated.

One disadvantage of all velocity modulation processes is the necessity of using high control voltages of the same order as the anode voltage. The maintenance of high control voltage and the capacitance of the electrodes results in considerable loading at high frequencies. For instance, with a control circuit capacitance of 50 cm., and a modulation voltage of 1 000, the consumption is 100 watts at a frequency of $3 \cdot 10^5$ cyc. The methods are therefore limited in practice to those special cases where the combination of luminosity and sensitivity is essential.

IV. Deflection of the Rays

Cathode rays are deviated in the deflection space by a transverse field which varies proportionally to the variable to be measured. Alterations in the deflection can be carried out by electrical or magnetic transverse fields. The laws underlying deflection and their exceptions, which occur under certain conditions, will be discussed in the following pages.

1. **Electrostatic Deflection.** (A) Theory. The behaviour of a cathode ray in a condenser field, as long as the cross-section of the ray is small compared with the distance between the plates, can be explained very well by the laws which a single electron obeys.

Fig. 59 shows the geometrical arrangement of the deflecting

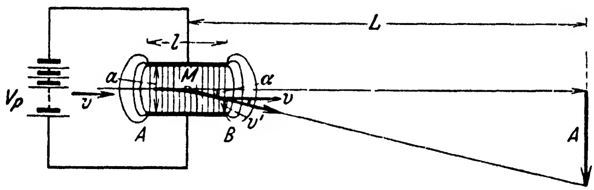


Fig. 59. Deflection of the Rays by an Electrostatic Field

field. The electron having a velocity v enters the field in a direction parallel with the plates. The field has been built up between the plates which are a distance a apart by an applied voltage V_p. It traverses the field in a time $t = 1/v$ where the plates are of unit length. The edge effect of the field of this plate is ignored. The subsequent motion is similar to that of a body falling under the action of gravity. A force $Ee = V_p e/a$ acts on the electron whose charge is e and mass m_0, giving a downward acceleration $g = (e/m_0)\,(V_p/a)$ where E is the field strength and a the distance between the plates. This acceleration g is constant in magnitude and direction during the whole time of flight t. Consequently, at the exit end of the field, there is compounded with the longitudinal velocity v a downward vertical velocity v' given by the relation

$$v' = gt = (e/m_0)\,(V_p/a)\,(1/v) \quad . \quad . \quad (23)$$

The diagonal of the parallelogram of velocities (in this case a rectangle) gives the required exit velocity $\tan a = v'/v$ in which the ray, after leaving the neighbourhood of the plates, proceeds

in a straight line. The curve traversed in the field is a parabolic trajectory. The tangents at the point of exit B intersect at the centre point M of the field. The ray appears to proceed in a straight line from the point M inclined at an angle a to the axis of the tube. Hence, for the deflection A on the screen, which is placed at a distance L from the centre of the plate, we obtain the relation

$$A = L \,.\, \tan a \quad . \quad . \quad . \quad . \quad (24)$$

Substituting the value found for $\tan a$,

$$A = lLV_p/2V_a a \quad . \quad . \quad . \quad (25)$$

after putting v in terms of V_a according to the relation $eV_a = \frac{1}{2}mv^2$.

The deflection of the spot is, therefore, directly proportional to the plate voltage V_p. In consequence, the cathode-ray tube possesses the very valuable property of recording time curves directly, i.e. without amplitude distortion. The deflection of the spot per volt A/V_p may be described as the sensitivity a_v of a cathode-ray oscillograph with electrostatic deflection, and this constant can be calculated fairly accurately in advance from the equation

$$a_v = lL/2V_a a \quad . \quad . \quad . \quad . \quad (26)$$

In practice a number of deviations from the theory developed under conditions which have been simplified are evident. They appear partly in gas-filled and partly in high-vacuum tubes.

One is due to the edge effect of the fields. The field does not begin and end at the edge of the plates, but extends some distance beyond. Particularly is this so in the case of short plates comparatively widely separated where l/a is small, in which case the theoretical relation gives too low a value. The discrepancy between calculated and measured deflection may amount to about 30 per cent. The deflection of the cathode ray in gas-filled tubes entails a certain consumption of power, since the conductivity of the space between the plates is not zero, as has been assumed theoretically, but depends on the voltage.

(B) Practical Measurements and Experiments with the Gas-filled Tube. It is difficult to calculate from theory the variations which occur in practice, but they can be easily measured. The essential basis on which the variations are detected consists of a graph of the plate circuit characteristic,

i.e. the relation between V_p and the current i_p flowing between the plates. A characteristic of the plate circuit with the circuit used for plotting it is shown in Fig. 60. The top plate, when positively biased, takes an electron current which approaches a saturation value of $25 \cdot 10^{-5}$ amp. This is of the same order as the total ray stream, although the ray does not visibly touch the plates. Even if the plate is negatively biased, the current reaching it does not fall to zero completely as its potential still remains positive to the electrons returning from the screen. A

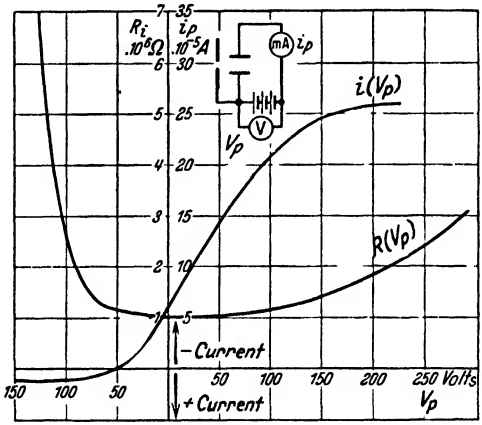


FIG. 60. RESISTANCE CURVE OF AN OLD TYPE OF GAS-FILLED TUBE (ARGON)

high negative bias in gas-filled tubes gives rise to an ion stream of about 1 per cent of the electron stream.

According to Fig. 60, therefore, the electron stream to the plates is only reduced to zero when a negative bias of about — 50 volts is applied. The plate system of the tube behaves, therefore, as if an applied e.m.f. of the same magnitude were present.

Apart from this internal e.m.f., it is possible to ascertain from the measured characteristic the effective internal resistance of the plate circuit. The resistance curve $R_i = f(V_p)$ is shown on the same graph. The shape of the curve shows that, as in this case, the internal resistance of tubes employing gas-focusing is of the order of 1 mΩ, the conductivity is a maximum with zero bias, i.e. when the ray is undeflected. In the case of large

deviations the resistance rises, though not proportionally, to a much greater value.

Assuming that the sensitive low voltage gas-filled tubes with anode voltages of 1 000 require on an average 100 volts for a full spot deflection, the maximum load is about 10^{-2} watts. This is very low, but in investigating voltages across resistances of about 10^6 ohms it may constitute a prohibitive load.

Perfect tracing can only be accomplished with gas-filled tubes under certain conditions, since the conductance of the plate circuit depends on the voltage. When the internal resistance of the circuit, the voltage across which is to be measured, is as great as or greater than the internal resistance of the plate circuit, distortion of the resulting curves is unavoidable.

The plate voltage is then a fraction of the test voltage and fluctuates with the deflection and gives rise to an unsuitable voltage division in the central position.

The tube would appear to be less sensitive in this position than in the one where the ray is deflected. This fault can be described as an *external* zero error. With sources whose internal resistance is not greater than one-tenth of the minimum plate circuit resistance, i.e. about 100 000 ohms, the error is small enough to ignore. It is only in exceptional cases, where the resistance of the measuring circuit is greater than 100 000 ohms, that any intermediate amplifier is essential. In the case of tubes discussed below, where there is a low current stream to the plates, the tubes can be connected to sources up to 10^6 ohms. Such tubes, therefore, when used in most low current investigations do not constitute any load on the circuit to be measured. One method of minimizing the external zero error is to bias negatively both plates at the same time. The characteristic of Fig. 60 shows, like the tube characteristic, two areas where there is excessive distortion. A rectifying effect may appear in these areas, and the whole curve can be displaced away from its central position as a result of the drop of voltage in the external resistance. Fig. 61 shows the plate circuit characteristics of Fig. 60 which are static curves with a superimposed constant alternating voltage V_P, the value of which is given as a parameter of each curve. The point of intersection of these curves and the resistance lines gives the alteration in bias, i.e. distortion caused by the biasing effect. In Fig. 61 there is a change in bias of 12 volts, with an external resistance of 10^6 ohms and an e.m.f.

of 20 volts (r.m.s.), i.e. about 60 per cent of the amplitude of the curve. With 60 volts and 10^6 ohms the bias is in the neighbourhood of 20 volts, whereas at 100 000 ohms external resistance the bias voltage is only 2 volts and can be ignored in practice.

The curves show that the internal resistance in the source of supply must not be too great.

Also in the case of tubes where there is only a small current to the plates the defect can be ignored.

Besides the so-called external origin error just mentioned, which occurs when the tube is coupled to an external current-carrying circuit, there is a similar *internal zero error* which is independent of the external circuit resistance. The internal zero error can be found by measuring the displacements with known sources of potential, the internal resistance of which is practically zero. The effect can be explained as an alteration of the internal field structure of the condenser caused by the gas-filling. It does not exist in high vacua. The field strength influencing the ray at the central point is less than that calculated theoretically for a vacuum. The explanation of this discrepancy lies in the fact that positive ions formed by the electron stream wander slowly to the negative deflecting plate, and the ejected electrons proceed quickly to the positive plate. As a result, a cathode or anode drop is formed in front of the corresponding plate so that the field in the centre area between the plates is reduced. The difference in velocities of the wandering streams causes a distortion of the field and the point of minimum field strength is not centrally situated with respect to the plates. The remedy suggested for the removal of external-origin-error—to bias all deflecting plates negatively with respect to the rays—gives some improvement, though not a complete cure, in the case of the internal origin-error, since the

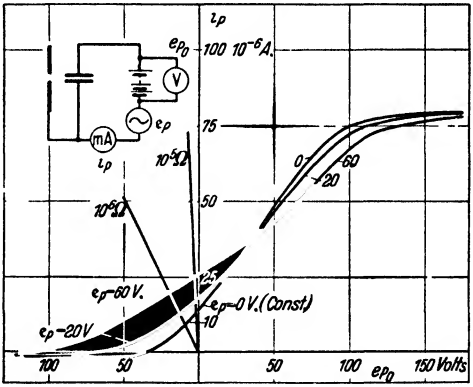


FIG. 61. LINEAR CHARACTERISTICS OF THE ANODE CIRCUIT

ion stream as well as the electron stream will be subjected to the influence of the plates. The difference between the field strength as calculated and as observed is dependent on the relation between the field resulting from the potential under observation and that due to the space charge. The greater the ratio between the former and the latter, the smaller is the origin error. As the field strength of the space charge increases with the electron ray stream, the origin distortion is only feebly apparent with small ray streams.(34) An increase in the electron velocity also reduces the amount of origin error since a more intense field is required to produce the same deflection. As the deflectional sensitivity depends on the time which is taken by the electrons to traverse the plates, and on the field strength due to the deflecting voltage, the length of the plates and their distance apart should be selected to be as small as possible to give the required sensitivity at a given anode voltage. Since the rays cover a considerable space when deflected a maximum limit is set to this distance.

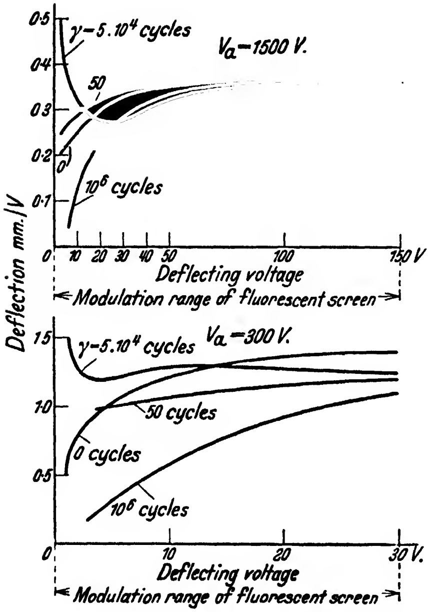


Fig. 62. Zero Error and its Relation to Frequency at 1 500 v. and 300 v. for a Normal Deflecting System (Argon Filling)

As the origin error is due to a certain extent to the charge of the positive ions in the deflection space, it depends naturally on frequency. Measurements of the origin error and the way in which it depends on frequency are given in Fig. 62. The upper curves were obtained with a tube having an anode voltage of 1 500 and the lower graph with an anode voltage of 300; the latter is taken from a work by W. Heiman.(35) These diagrams show that the deflectional sensitivity increases with

the voltage for all frequencies except in the region of about $5 \cdot 10^4$ cyc.

The remarkable behaviour in the region of medium frequencies which always occurs when positive ions are influenced simultaneously (Wehnelt cylinder control, external control,

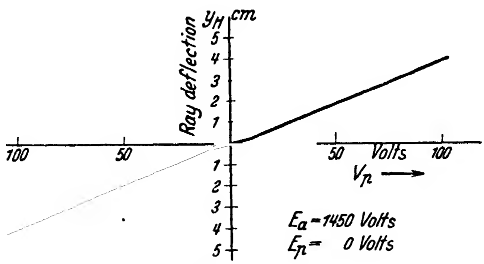


FIG. 63. SENSITIVITY CURVE MEASURED UNDER STATIC CONDITIONS

etc.) commences when the deflection period corresponds to the time of passage of the ions. Both diagrams also confirm what has been stated above, that the range of the origin error in point of space is much smaller with high than with low anode voltages.[36]

The part played by internal origin error in distorting the sensitivity curve of a standard gas-filled cathode-ray tube having electron velocities of 1 000 volts is shown by static measurements in Fig. 63. In this case the deviation was measured by the application of varying d.c. voltages from a battery. Another dynamical trace of the spot is shown in Fig. 64 and was photographed while the tube was in action. This last curve was obtained by applying to both pairs of plates voltages of equal amplitude (frequency 50 ~) from a discharge circuit, the rate of voltage rise of which was constant. The measurements made with direct voltages as well as the curves obtained under dynamic conditions, show the bend in the sensitivity curve very

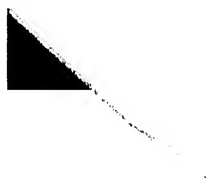


FIG. 64. STRONGLY PRONOUNCED BEND IN THE SENSITIVITY CURVE OF AN OLD TYPE OF GAS-FILLED TUBE

distinctly. The improvement obtained by an equal negative bias to the deflection plates with respect to the anode is shown in Fig. 65, which is a fluorescent screen photograph, and shows various deflection curves. The various curves differ from one another in respect of the varied bias on the plates—the bias increasing negatively from right to left. The second curve from the left in Fig. 65 was taken with a bias of 200 volts with respect to the anode, and shows a considerable portion which is a straight line. This proves that the internal origin error can be reduced by negative biasing to such an extent as

FIG. 65. PHOTOGRAPHED SENSITIVITY CURVES FOR DIFFERENT VALUES OF PLATE BIAS WITH RESPECT TO THE ANODE

to be of little importance in most measurements. There is a method due to Bedell and Kuhn[37] which eliminates both internal and external origin errors, and consists of applying a high negative charge to one of the plates of each pair with the object of displacing the electron jet from the anomalous centre of the plate field to the undisturbed periphery. Since the fluorescent spot must, from practical considerations, be kept at the centre of the screen, it is essential either for the tube itself to be constructed on non-symmetrical lines or for the electrostatic displacement to be eliminated by means of an auxiliary magnetic field. It is easy to produce an auxiliary magnetic field in a tube having a nickel anode. It is only necessary in such cases to magnetize the anode permanently (see below).

Furthermore, Hudec[38] has suggested that electrical instead

of magnetic return conductance could be used by means of one or perhaps two additional pairs of plates. With electrical as well as magnetic return conductance, the fundamental disadvantage is that the intensity and direction of the return conducting field must be adapted to the bias voltages employed. Further, if the return voltages approximate to the bias voltages when electrical control is used, the deflecting system will have angles of deviation whose greatest value will be much less than with a normal plate system of equal sensitivity. To secure deflecting angles of the same magnitude, it is necessary to double the distance between the plates which results in the sensitivity being reduced by 50 per cent. Besides the methods described, which are nearly all designed to displace the zero error to the edge of the screen, other means are also possible in which the deflecting field is superimposed on a condenser field whose intensity changes from high positive to high negative values, or vice versa, in the direction of the length of the plates. This suggestion can be realized by creating a voltage drop along the deflecting plates which must be made of resistive material or, alternatively, along one plate of each pair. This arrangement leads to a perfectly regular distribution of space charge effect over the screen surface as long as the voltage drop along the deflecting plates is greater than the amplitude of the deflecting voltage.

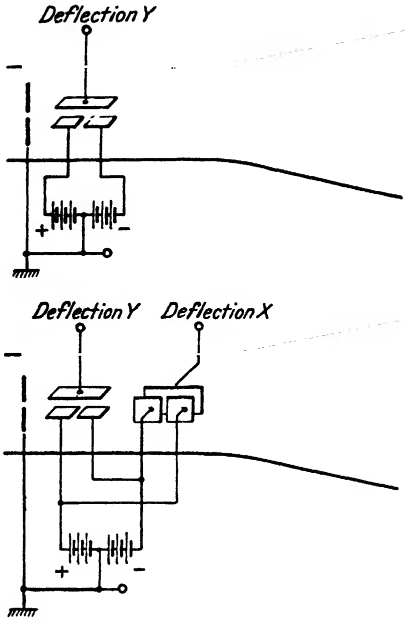


Fig. 66. Circuit of the Deflection Plates in a Gas-filled Tube with Divided Earth Plates without Zero Error

The diagram, Fig. 66, gives the basic idea of a similar but simpler solution.[39] It consists of dividing one of each of the pairs of plates of the deflecting system—preferably the one

connected to earth—and taking the two halves to different d.c. potentials. In the circuit of Fig. 66 the deflecting field is superimposed simultaneously on two fields of equal but opposite intensity. If, by suitable choice of sufficiently high voltage from the auxiliary battery, the bias voltage is always greater than the deflecting voltage (in order that the intensity of the deflecting field on any part of the system does not at any time become zero), then the zero error will on both sides lie outside the fluorescent screen image. This is distinct from the older process mentioned above, where the error is almost always on one side. The path of the ray which results from this system may be explained by the aid of Fig. 67 (a). If we consider at first only one part of the deflecting plate system, the deflection a corresponding to the intensity and direction of the field takes place. The ray would then continue to travel in the direction of the straight lines. If, now, the second part of the deflecting system is considered by itself, a deviation through the angle a'' occurs in the opposite direction. These angles are equal if the lengths of the subdivided pairs of plates are the same. If the ray traverses both fields in succession, a greatly extended path is obtained and it can be seen that the original direction is resumed.

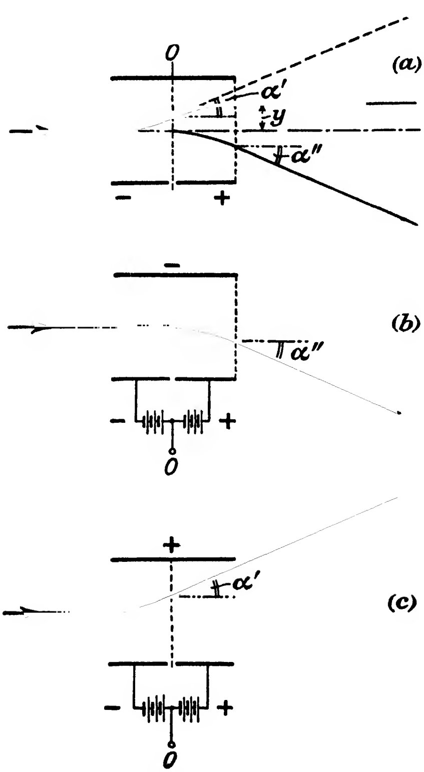


FIG. 67. RAY PATH WITH DIVIDED EARTHED PLATES AT DIFFERENT DEFLECTION VOLTAGES

The parallel displacement which occurs, and which amounts to y, can be ignored in comparison with the deflection on the

screen. In order to prevent a reduction in the maximum ray deflection due to parallel displacement, it is advisable to adjust the ray in its stationary position so that it is slightly nearer one side of the plates, and that the emergent ray which has

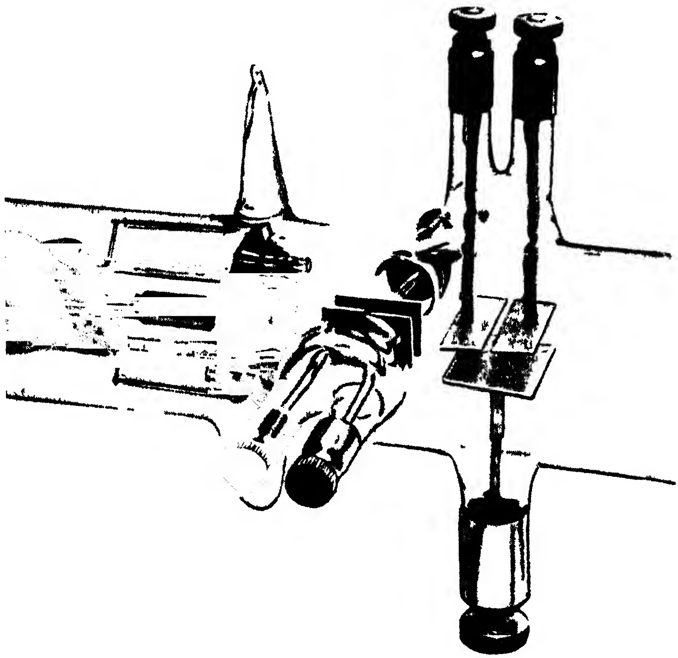


FIG. 68 ELECTRODE ARRANGEMENT OF A TUBE FOR OPERATING WITHOUT ZERO ERROR

suffered parallel displacement lies exactly on the axis of the deflecting system. Whereas in Fig. 67 (*a*) the path of the ray is traced to show the superimposed effective deflection field as zero, Fig. 67 (*b*) shows the path of the ray in the case where the effective deflection field strength just reaches that of the first part of the deflection system, but in the opposite direction, and in Fig. 67 (*c*) the action of the second part of the deflection system.

In the two cases illustrated, the deflecting fields oppose one

another in one part of the system and assist each other in the second part. If the voltage of the auxiliary battery is chosen higher than that given above, an unnecessarily large parallel displacement will occur. On the other hand, if it is made smaller, the zero error will leave the two edge areas and move towards the centre of the screen. It does not, however, cause anything like the disturbance which occurs in the ordinary method of operation as long as the auxiliary voltage is sufficiently high that the disturbed zones do not coincide or overlap each other. The explanation is that at this voltage

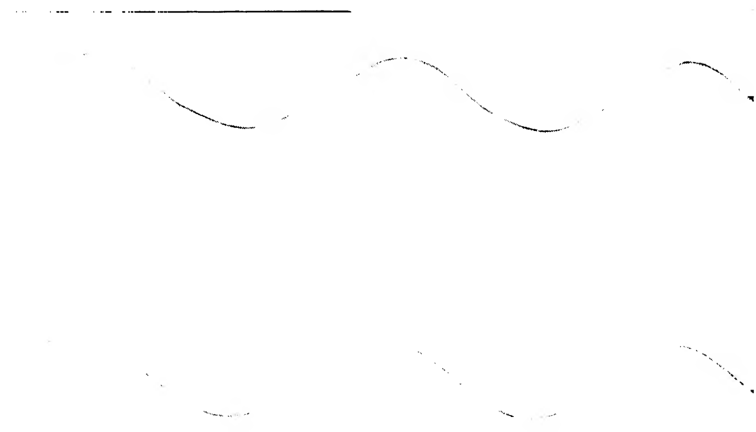


FIG. 69. OSCILLOGRAMS OF A SINUSOIDAL VOLTAGE WITH ZERO ERROR (*above*) AND AFTER ITS REMOVAL (*below*)

one at least of the two parts of the system always operates free of distortion. In practice, with a tube for deflecting in both directions as in Fig. 66, the two parts of the plates which are at the same potential can be connected together. The number of leads coming out is then no greater than in a cathode-ray tube of normal construction. Internal connexion would appear to be desirable in such cases as those where the tube is only to be used for certain purposes. For universal use, it is better to lead out the two parts of the plate separately. Fig. 68 illustrates the deflecting system of a tube incorporating the fundamental ideas mentioned. If the zero error can be ignored, this tube can be employed like an ordinary type if both halves of the plate are connected together externally.

The difference is clearly shown in the curve of the oscillogram of Fig. 69. Both curves were traced in the same tube by the same sinusoidal voltage. The upper wave, which appears to contain harmonics, was obtained by connecting the two plate sections of a gas-filled tube according to Fig. 68, and the lower curve was traced without distortion by introducing an auxiliary voltage according to the circuit of Fig. 66. By means of the simple suggested alteration to the deflecting system it is possible to eliminate the distortion due to space charge in a gas-filled tube, without dispensing with the symmetry and clarity of the arrangement.

As we have seen, there is a number of discrepancies between calculated and measured values, especially in gas-filled low voltage tubes. It is highly important, therefore, to collate observed measurements. In order to correct the sensitivity formula empirically, it is necessary to collect the measured variations on a graph. The sensitivity constant a_v was calculated and measured for a number of tubes of widely differing dimensions. Measurement was made by applying to the tubes 3 or 4 known deflectional a.c. voltages of audio frequency. The results of the measurements were plotted against the "field shape" as abscissae in Fig. 70. All measurements were reduced in terms of a standard bulb of length $L = 300$ mm. and a normal anode voltage of $v_a = 1\ 000$. It is apparent that when $l/a < 2{\cdot}5$ the measured values are too great and when $l/a > 2{\cdot}5$ they are too small. As already implied, the error is due in the one case to field edge effects and on the other to origin distortion. The graph of Fig. 70 corresponds to the scale of Fig. 71. As can be seen, the variations amount to 50 per cent maximum.

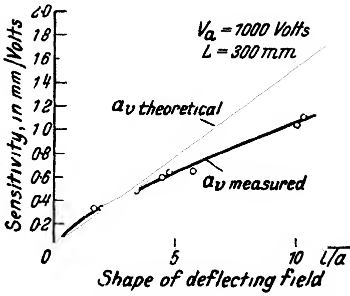


FIG. 70 MEASURED AND CALCULATED VALUES OF SENSITIVITY

Occasionally deflecting plates are dispensed with and an external control used. In principle there is no difference in effect between the field produced by plates inside the tube and external control, but in practice the latter causes some difficulties in gas-filled tubes which have to be considered.

Externally controlled gas-filled tubes are not equally efficient at all frequencies. On account of the low sensitivity, external control is unsuitable for low frequencies up to 5 000 cyc. as shown in Fig. 72. The conditions in a high-vacuum are very much more favourable, but here as a rule the uncertain charges on the wall of the bulb produce a distortion of the electron-image.

If the velocity of the wandering ions is sufficiently high to allow them to reach the glass wall in less than the time of one

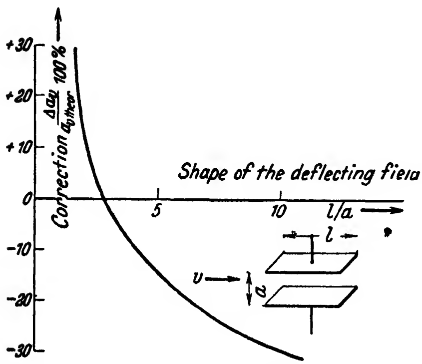


FIG. 71. DEVIATION OF SENSITIVITY FROM CALCULATED VALUES

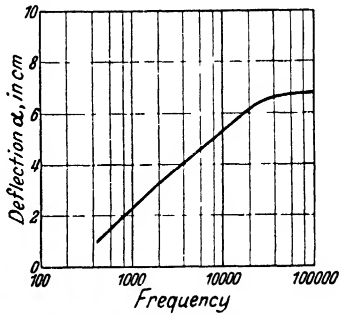


FIG. 72. RELATION BETWEEN FREQUENCY AND ELECTROSTATIC DEFLECTION BY EXTERNAL ELECTRODES OF AN OLD TYPE GAS-FILLED TUBE

cycle, then the current which is being influenced by the external electrodes will neutralize the charges on the wall of the bulb. It is only at really high frequencies, say, 100 000 cyc., that the externally controlled tube reaches the limit of its sensitivity. Up to that limit the empirical relation

$$a_v = k \,.\, ln \,.\, f \qquad . \quad . \quad . \quad . \qquad (27)$$

holds good, in which the frequency factor k depends largely on gas pressure, conductance of the glass, etc. The externally controlled tube is very suitable for high-frequency investigations. It has the advantages of simple construction and of ease in adjustment of sensitivity by moving the plates.

When the electron stream is deflected in a gas-filled tube two other phenomena which reduce the accuracy of measurement make their appearance. A photograph of the result of one effect is given in Fig. 73. If the cathode ray is allowed to scan the screen surface, as for instance in producing a line

raster in which the velocity in the direction of the line is about 100 m./sec., additional oscillations occur as can be seen from Fig. 73. These disturbing oscillations occur in the older type of tube as soon as the anode voltage exceeds about 2 000. The frequency of the disturbing oscillations is definite, and only slightly altered by change in pressure or current, and is of the order of 50 kc. The direction of the oscillation amplitude is always radial from the centre point of the screen. The ray behaves as though the velocity were modulated a few per cent, by the frequency in question. The phenomena observed are as the result of charges on the glass walls of the tube, caused by diffused or secondary electrons. When these charges reach

FIG 73 RASTER OF AN EARLY FORM OF GAS-FILLED TUBE DISTURBED BY IONIC OSCILLATIONS

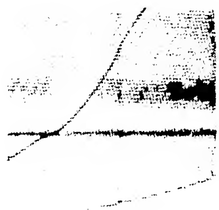


FIG 74 RASTER WITHOUT IONIC OSCILLATIONS BUT WITH STRONGLY PRONOUNCED ZERO ERROR IN A GAS-FILLED TUBE

a certain value they are neutralized by positive ions present in the gas. The periodic deflection of the cathode-ray which occurs in this way can be eliminated by an earthed metallized coating on the external surface of the glass, as in this way these charges are fixed capacitatively or conducted away. It is certain that external metallizing eliminates the extra deflection and the raster then appears without ionic oscillations, as shown in the photograph of Fig. 74. In place of external metallizing metal foil placed round the neck of the tube and earthed (as in Fig. 75) often suffices.

A further anomaly occurs when an attempt is made to use gas-focusing with high-speed rays. An interesting case is illustrated in Figs. 76 (*a*) and 76 (*b*). A point which is itself sufficiently sharp, in Fig. 76 (*a*) traces a 50 cyc. oscillation, and in Fig. 76 (*b*) a 10^6 cyc. oscillation. The amplitudes are almost

the same. The low frequency is reproduced to the same degree of sharpness as that to which the stationary spot was adjusted. The h.f. oscillation on the other hand appears very much diffused. In the central portions, i.e. where the tracing speed is highest, the sharpness has suffered most. This can be partly removed by increasing the emission. It is also apparent that

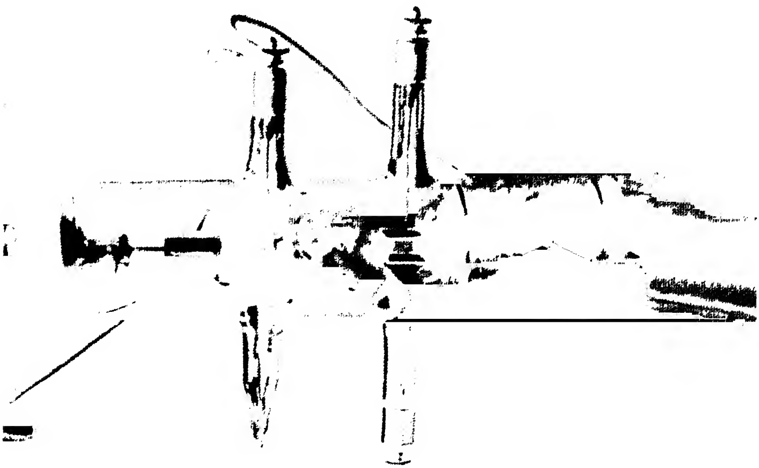


FIG. 75 CONNEXION OF AN EXTERNAL EARTH TO THE NECK OF THE BULB TO SUPPRESS GAS OSCILLATIONS

by filling the tube with a gas of low molecular weight, e.g. hydrogen, as compared with argon, the h.f. limit at which de-focusing takes place can be increased considerably. In the case in question, it was possible to obtain a sharp tracing with a 2 cm. stroke up to almost 200 m. wavelength. By observation it is possible to distinguish in practice between two conditions of gas-focusing—

(*a*) Gas-focusing with single sweep.
(*b*) Gas-focusing with repeated tracing.

The single sweep also includes the tracing of low-frequency oscillograms in which the period is long compared with times occupied by the space charge in building up and disappearing. Repeated tracing includes the case where the period is short

or of similar magnitude to the time in which the space charge builds up. In order to obtain optimum gas-focusing, the greatest possible space charge must be created in the first as well as in the second case. The only difference in the second case of the above detailed considerations is that the positive space charge does not confine itself to the small volume of the interior of the ray, but to the large volume of the entire space traversed by the ray. This latter volume, of course, becomes greater the longer the oscillogram. It can be seen that in the second case

(a) (b)

FIG. 76. BLURRING AT HIGH TRACING SPEEDS AND GAS-FOCUSING
(a) Sharp stroke at 50 c.p.s., (b) blurred stroke at a deflection frequency of 10^6 c.p.s.

a much larger number of ions must be produced (e.g. by greater ray currents, choice of suitable gases, higher pressure, and the anode voltage within certain limits. That ample gas-focusing is also secured under the second condition of operation is proved by measurements in the range of metre and decimetre waves which have been carried out successfully with gas-filled tubes. (H. E. Hollmann, 80 cm.) Between the two zones discussed, there is a range which with the usual lengths of oscillogram embraces the frequency range 10^5–10^6 cyc. This is the zone which embraces the broadcast frequencies, and is therefore of particular technical interest. For measurements in this range of frequency the gas-filled type, even with electron-optical system and reduced gas pressure, is quite unsuitable. For h.f. measurements—and always if high accuracy of measurement is demanded—the high-vacuum type should invariably be used

since it avoids almost all the errors mentioned in this section; and when the deflection space and the conditions under which it operates are correctly designed, it always has a high and constant spot definition.

(c) Investigations with the High-vacuum Tube. In contrast to the gas-filled tube with its focusing effect, the conditions of deflection in the high-vacuum tube are of great importance for the design of the ray-producing system. The questions relating to deflection cannot therefore be treated alone here, but only in conjunction with the other factors which influence the system.

The efficacy of large angles of convergence of the electron beam between the electron-optical system and the fluorescent screen has already been mentioned above. Large angles of convergence are advantageous for the development of the ray-producing system, since the resulting angles of divergence depend upon it. The angle of convergence determines the cross-section of the electron beam at the point where the deflection takes place, as well as the cross-section of the electron-optical system which is usefully employed and which does not generally differ greatly from it, since the distance from the deflecting point or the centre of the electron-optical system—which is practically the same—to the screen is generally considered fixed. Fig. 77 shows the simple geometrical relations. The distance between the screen and the centre point where deflection takes place is determined by the dimensions of the image, which is to be considered as being sufficiently free from distortion. Both in tracing and visual observation, distortion is now considered sufficiently small if this distance is about double the diagonal of the television picture or screen image. Greater distances are to be avoided since the distance between the screen and the electron-optical system, in order to secure small spots (low magnification), is always kept as small as possible. Even the demand for greater deflectional sensitivities in vogue to-day would not justify its increase, since experience has shown how to provide the necessary deflecting fields economically.

The efficacy of large angles of convergence has already been referred to above, and it remains to answer the question, what is the greatest value permissible? As the distance of the image according to the above is to be considered fixed, it is only necessary to make clear what ray cross-section may be used

at the point of deflection without the spot being enlarged beyond its critical size, which may be considered as the case when the diameter is greater than the diameter of an elemental area of the television picture at the edge. The greater the angle of convergence, the more easily a decrease in spot definition occurs at the edge of the screen. The greater the cross-section of electron beam at the point of deflection, the

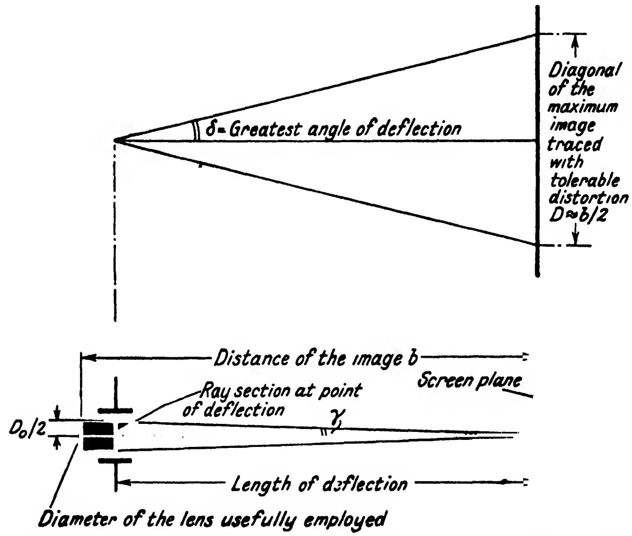


FIG. 77. THE VARIOUS MAGNITUDES OF THE DEFLECTION SPACE

more easily will irregularities in the deflecting field produce a critical enlargement of the spot.

In order to develop the electrostatic deflecting field so that disturbance of the image formed by the electron-optical system does not take place, the mean potential of both deflecting plates must be constant with respect to the ray. This mean potential must be the same as that of the main anode. Attention need not be given to this point in the case of gas-filled tubes, since the ray has a very small cross-section at the point of deflection. Consequently, it is usually sufficient to employ the circuit of Fig. 78 with a gas-filled tube, one deflecting plate being connected direct to the anode or earth and the deflecting voltage taken to the other plate. Owing to the large cross-section of the ray in the high vacuum tube, this unsymmetrical

arrangement and the large emergent angles which the ray stream follows results in an elongated spot, and this cannot, even by subsequent adjustment of the focal length of the electron-optical system, be brought to the sharpness existing at the centre of the tube. The deflecting plates act like a cylindrical lens. This disturbance in forming the image, as shown by experiments, can be eliminated entirely by adopting the symmetrical arrangement of voltage illustrated in the lower part of Fig. 78. If the measuring arrangement or the operating circuit does not provide a deflecting voltage symmetrical to earth, such a condition can be created by the simple preliminary push-pull stage discussed in later chapters. If the maximum angle of convergence with the type of tube available is not very great, and if the measurement is limited to relatively low deflecting voltages which only partly modulate the fluorescent screen, the decrease in the efficiency of the spot in unsymmetrical operation very often can be ignored.

This applies, however, only if one pair of plates is provided, or to that pair of plates which is on the side of the fluorescent screen. If the deflection voltage is practically symmetrical, and the dimensions of the deflecting plate are such that there is only a slight disturbance from the field of the edge, then perfect operation with large emergent angles and angles of convergence up to 1° are possible. In practice, it is generally the rule to work with smaller angles of convergence in order to retain somewhat greater sharpness and prevent the remaining dissymmetry of the system, small errors in adjustment of the lens voltage, and variations in the length of path, from exerting too great an effect. In tubes where the distance between the screen and the point of deflection is about 30 cm. the minimum section of the ray at the point of deflection in the larger and better types is of the order of 4–8 mm.

In the section on control of the ray energy it was pointed out that the shape of the ray is, as a rule, changed by the brightness control. This takes place in such a way that with a strong negative bias a very small cross-section exists at the plane of the lens as well as at the point of deflection. If symmetrical voltages are not available, the cross-section of the ray in the high-vacuum tube can be reduced by using strong negative bias voltages until a sharp image is obtained, even with the greatest angles of emergence. Nevertheless, the spot brilliancy is for many purposes already too small for this

method of control to be used except where very high anode voltages are employed.

The oscillograms reproduced in the following sections show that, with symmetrical voltages, a constant sharpness of the spot over the entire screen surface, with high brilliancy, can be secured; the oscillograms show, further, the entire absence

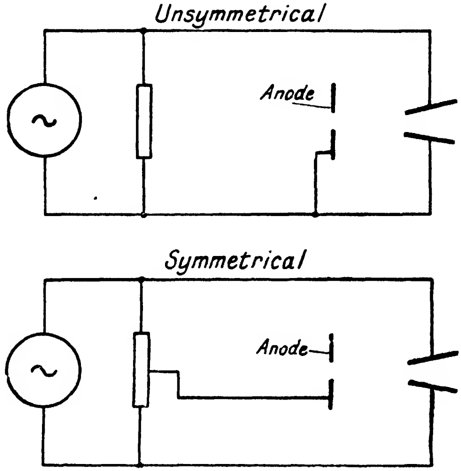


FIG. 78. SYMMETRICAL AND UNSYMMETRICAL ARRANGEMENT OF THE PLATE CIRCUIT FOR ELECTROSTATIC DEFLECTION

of anomalies and distortion in deflection. Only one source of error needs mention in this connexion. The secondary electron stream returning from the screen very easily produces charges on the interior surface of the glass, particularly when the value of D for the anode with respect to the screen is not negligible. In the high-vacuum tube the charges on walls are neutralized comparatively slowly, and can therefore give rise to raster distortion, for instance in television pictures, and even to slow oscillations of the whole image. Experiments have shown that it is not necessary to metallize the tube internally to get rid of the wall charges, but that it is sufficient to make them constant by a capacitance to earth consisting of an earthed external metallic coating. Such external metallic coatings are visible in the tube shown in Fig. 80. If the secondary electron stream has not already been conducted away by internal metallizing, a certain proportion of the return electron current reaches the deflection plates determined by the value of D in question.

With the small currents present in a vacuum tube the amount of current reaching the deflecting plates is never sufficient to cause any appreciable voltage drop over the terminal resistances when these are several megohms. Here, again, the vacuum is vastly superior to the gas-filled tube. For measurements of higher accuracy it is desirable not to make the resistance in the deflecting plate circuit greater than 500 000 ohms. In cases where the resistance in circuit with the deflection plates must be very small, the current taken by the deflection plates, which are always positive, can be kept very low by means of internal metallizing, trap, or guard-ring electrodes arranged between

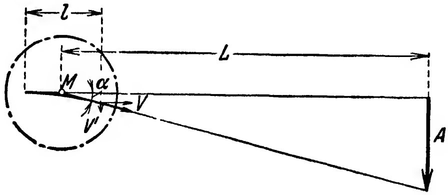


FIG. 79. DEFLECTION OF RAY BY A MAGNETIC FIELD
(Field perpendicular to plane of the paper)

the deflecting plates and the screen, or by a screen to which a separate connexion is made.

2. **Magnetic Deflection.** (A) THEORY. Calculations will be made on the assumption of the existence of a uniform magnetic transverse field to which the ray is exposed over a length l of its path. The strength of the field H is found from the current i flowing through the exciting coil. Here, again, it is possible to obtain an approximation to the true result by applying the laws to a single electron. The force acting on a part of the ray stream $i \,.\, l$ and being perpendicular to the direction of the magnetic field is

$$K = H \,.\, i \,.\, l \qquad . \quad . \quad . \quad . \quad . \quad . \quad (28)$$

and the acceleration of the electron is

$$g = K/m = Hil/m = Hev/m \qquad . \quad . \quad . \quad (29)$$

The final velocity v' which the electron reaches in time t under the force K

$$= v' = gt$$
$$= (Hev/m)\,(l/v) = (Hel/m) \qquad . \quad . \quad (30)$$

From this it follows that the direction of motion at the point of emergence makes an angle a with the original direction given by the relation

$$\tan a = v'/v = (He/m)\,(l/v) \qquad . \quad . \quad . \quad (31)$$

The geometrical similarity of the small triangle and the large one with base L and spot deflection A gives for the latter the relation

$$A = (He/m)\,(lL/v) \qquad . \quad . \quad . \quad . \quad (32)$$

With magnetic deflection the sensitivity is

$$a_m = A/H = (e/m)\,(lL/v)\ (\text{mm./gauss}) \qquad . \quad (33)$$

As we have seen, the magnetic sensitivity is proportional to $1/v$ and not $1/v^2$ as in the case of electrostatic deflection. Small variations in velocity, therefore, have much less effect in magnetic than electrostatic deflection. Variations from this theory must be expected and are evident from the approximations which have been assumed. They are the same as with electrostatic deflection and can be understood from the calculations. The edge effects of the field cause considerable variation under certain conditions, especially when the external field, on account of the exciting coils, influences the undeflected ray. Also, it is not an easy matter to maintain a uniform deflectional field over the whole operating length l, so that a different value representing the effective length will have to be substituted in place of the geometrical length. More exact details should therefore be obtained from experiment.

(B) Practical Results. Magnetic deflection is free from the disturbances caused by reaction of the cathode ray on the current circuit, and from such tracing defects as are discussed above. A further advantage is that it is a method of controlling the tube from the outside, since it is a simple matter to adjust the position of the exciting coils and to change them. The fact that the impedance of the coil depends on the frequency is a disadvantage. When endeavouring to obtain a current sensitivity which is constant over a wide frequency range, it is desirable to connect a non-inductive resistance which has a value greater than the coil impedance ωL in series with it. Of course, the power consumption of the deflecting system will be greatly increased. Sensitivity and independence of frequency are not easily attained simultaneously with magnetic deflection.

The following numerical example gives some idea of the conditions under which magnetic deflection is carried out.

The mean sensitivity of coil deflection is about 1 mm./mA. with an electrode voltage of 1 000, the effective length l is 60 mm., the length of the ray 300 mm., and number of turns 600. Suitable inductance would be about 0·02 henry with an

FIG. 80 ARRANGEMENT OF DEFLECTING COILS FOR A TELEVISION TUBE

impedance of 1 200 ohms at the highest audio-frequency of 10 000 cyc. With an additional resistance of 10 times the impedance of the coil, a spot independent of frequency necessitates a power consumption of 20 watts, which obviously cannot compare favourably with the efficiency of electrostatic deflection.

As the equations given above show, the deflectional sensitivity and consequently the output required depend to a great extent on the proximity of the deflecting coils to the ray. To get higher sensitivity with magnetic deflection, therefore, the procedure of constricting the neck of the bulb between the

source of the rays and the screen has been resorted to. As long as the diameter of the neck is not much greater than 5 cm. the output required for a suitably-formed deflection of a saw tooth oscillation of only 25 periods (i.e. a saw tooth oscillation as required in television for the picture frequency) is quite low enough to come within the range of standard small broadcast amplifying valves.

In these and similar cases where a deflection scans with frequency components below 500 cyc., magnetic deflection is superior in many ways, even to electrostatic deflection. The use of two deflecting coils as indicated in Fig. 80 produces

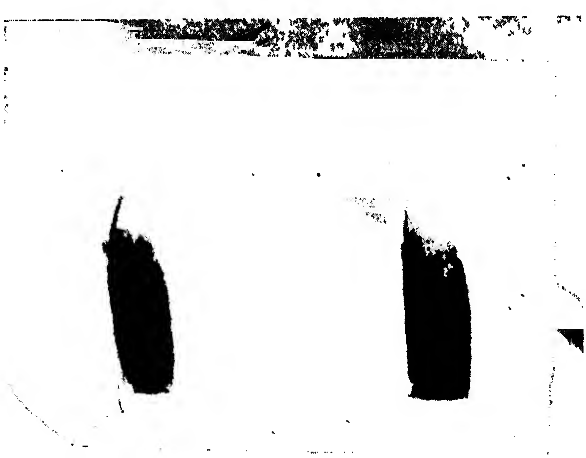


FIG. 81 ARRANGEMENT OF THE COIL WITH IRON CORE FOR MAGNETIC DEFLECTION

very uniform fields, even in larger spaces in the vicinity of the axis of the tube. This characteristic of magnetic deflection is of very great value in modern high-vacuum tubes where the cross-section of the ray at the deflection point is large. Magnetic deflection is more economical where an iron core is used in the coil. The form of such a core is illustrated by way of an example in Fig. 81. The iron core should be designed so that iron losses can be ignored even when higher frequency components are present. The smaller the diameter of the neck of the tube, the greater the improvement attained by the use of an iron core, i.e. by reducing the magnetic reluctance of the

external circuit. If high accuracy of measurement is required, it is advisable to dispense with the iron core which in practice is never completely independent of amplitude and frequency.

3. Composite Methods of Deflecting the Rays. (A) DEFLECTION IN CARTESIAN CO-ORDINATES. It is possible by using only one deflecting field to obtain photographs of time curves when investigating low frequencies. The missing co-ordinate, the time abscissa, would, in such a case, be replaced by a revolving mirror or other external optical apparatus, which would be situated between the observer and the visible record of the test. Mechanical methods of this kind are useless for high frequencies. We can take, for example, the case of photographing a 100 m. wave with an amplitude of 10 cm., which is recorded at a maximum tracing speed of 2 000 Km./sec., itself a high speed; whereas in investigating transients in high-voltage tubes, tracing speeds up to one-third the velocity of light are the highest speeds attained with cathode-ray tubes. In making high-frequency investigations we are forced to replace the time co-ordinate by an electrical deflection of the ray, transverse to the direction of deflection due to the voltage under test. The voltage producing this transverse field must have a known, and if possible, linear variation with respect to time, so that the resulting curve shows at once the test voltage to a time base.

The problem consists, therefore, in giving the ray two deflections in fixed directions to one another, and these deflections must be quite independent. With few exceptions both deflections should be arranged along axes which are perpendicular to one another. In many cases, particularly in phase measurements, conditions must be such that deflections can be made in both directions simultaneously. The deflections can be made by two electrostatic or two magnetic fields at right angles to one another, or by one magnetic and one electrostatic field acting in parallel directions. In principle the fields can act simultaneously by superposition, or can be placed one behind the other in the direction of the ray. The particular difficulties of both methods are explained in Figs. 82 and 83. Fig. 82 shows two crossed electrical fields operating simultaneously which are produced by a box-like arrangement of four condenser plates.

Fig. 83, on the other hand, shows the more usual arrangement of the crossed fields one behind the other.

The box-like arrangement does not ensure complete independence of the two fields from one another. On the right of Fig. 82 the configuration of the field resulting from the short-circuiting of the pair of horizontal plates is shown as

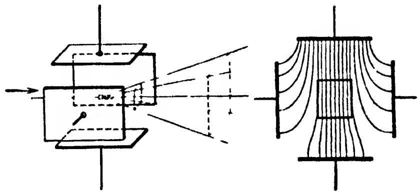


FIG. 82. SIMULTANEOUS EFFECT OF TWO ELECTROSTATIC FIELDS AT RIGHT ANGLES TO EACH OTHER BY MEANS OF A BOX-LIKE ARRANGEMENT OF DEFLECTING ELECTRODES

an end-on view. It is assumed that one pole of each voltage component is earthed. It can be seen that the ordinate field which would be uniform over the whole width of the plates if the other field were absent, becomes distorted by the two opposite plates, and there remains only a limited portion of the field in which uniform deflection can be obtained. The

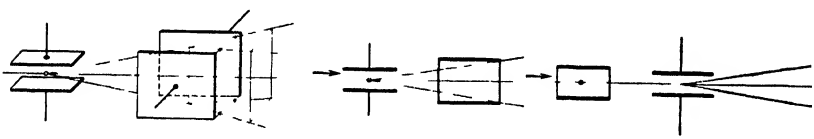


FIG. 83. SUCCESSIVE EFFECT OF TWO SEPARATED PAIRS OF DEFLECTING PLATES

The two most important cases

rule for the arrangement shown in Fig. 82 is therefore that the maximum final deviation must never overlap the edge of the plate. The conditions of Fig. 82 are rather better when the voltage is taken to the deflection plates symmetrically.

Superposing the two deflecting fields on one another (Fig. 83) does not cause any interference, but the distance between adjacent edges of the plates must be greater than the spread of the field. The width of the plates which in Fig. 83 give the first vertical deflection need only be very small and a few times larger than the diameter of the ray; the width of the second pair of plates must be larger so that even under greater deflection of the first pair of plates the ray does not pass beyond the edges. The disadvantages of the use of staggered

fields for deflection are that their sensitivities differ, by reason of their different distances from the screen, internal phase differences in the fields are set up as a result of the electron velocity and axial displacement of the ray occurs even when the fields are actually in phase.

The latter becomes of importance when registering high frequencies with slow cathode rays (see below).

The same considerations and sources of error apply in principle to crossed-magnetic fields. The use of an electrostatic and a magnetic field at the same time has one advantage. Both fields can be superimposed at the same point without mutually disturbing one another.

At this point mention may be made of the fact that inclination of the deflecting plates has proved extremely useful in securing higher deflection sensitivity at given maximum angles of emergence, particularly in tubes for larger ray deflections. Progress has not been so great, however, with the low voltage tube as with the high voltage oscillograph, where detailed calculations as to the most favourable kind of plate, i.e. the type of plate most suited to the parabolic path of the electron in the deflecting field, have been carried out. On the other hand, efforts have been made with the low voltage tube to obtain a constant deflectional sensitivity for any position of the ray by forming the plate edges into definite curves.

When the deflecting plates are used asymetrically, and the angles of deviation are large, a trapezium instead of a rectangular figure is observed even when time deflections from constant discharge voltages are used. This is due, when electrostatic deflection and unsymmetrical operation is used, to the electrons reaching the second deflecting system with different velocities according to the direction in which the first deflection took place. These phenomena are closely linked up with the fact that in the high-vacuum tube, where dual electrostatic deflection takes place, a symmetrical disposition of voltage on the pair of plates facing the anode is absolutely essential. As time voltages are usually more easily produced symmetrically than measured voltages, it is advisable in high-vacuum tubes to connect the time base to the pair of plates facing the anode.

We must not omit to mention that slotted discs at anode potential have been used for de-coupling and screening several pairs of plates.

Although perfect rasters or measurement figures can be obtained with a symmetrical arrangement of voltage and dual electrostatic deflection over the whole screen, and although tubes are not much more complicated by building in two further plates which are led out separately, yet television tubes of normal construction developed by the author and discussed below in which both electrostatic and magnetic deflection are used, are to be preferred.

Others recognized at the same time as the author that this arrangement is very effective for television reception.[40] Where

FIG. 84. SHARP AND UNDISTORTED PICTURE RASTER FROM A HIGH-VACUUM ELECTRON-RAY TUBE OF MODERN CONSTRUCTION

both electrostatic and magnetic deflection are used, which is possible with modern apparatus for producing saw toothed oscillations without any great increase in power consumption, there is the additional advantage to that mentioned above, of a smaller image distance, with equal length of deflection, which is maintained as a result of the reduced length of the second deflecting system. Care must be taken, of course, that the magnetic deflecting system does not disturb the system which is the source of the rays. This condition is usually satisfied completely when the neck of the tube is similar in size to that in the tubes discussed below, if the line connecting the centre of the coil coincides with the edge of the deflecting plates which face the screen. The uniform sharpness of the spot which is obtained with composite deflection right up to the extreme edge of the screen, can be seen from the raster photograph of Fig. 84. A comparison of this picture, which is uniformly good, with that

from a gas-filled tube reproduced above, shows the enormous superiority of the high-vacuum over the gas-filled type of tube.

(B) Deflection in Polar Co-ordinates. The combined deflections so far discussed have all been made in rectangular co-ordinates. A description of the way in which polar co-ordinates are used is also given here.

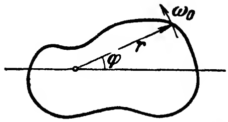


Fig 85 Representation in Polar Co-ordinates

As shown in Fig. 85, the principle of this method of tracing is that a rotating voltage vector r with constant angular velocity varies in length to correspond with the voltage under test. The angular velocity corresponds to the frequency ω of the variable under test or to some exact sub-multiple of it if a standing figure is to be produced.

Oscillography in polar co-ordinates is carried out with two

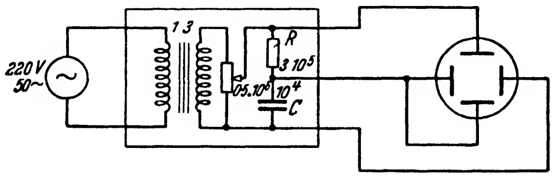


Fig 86 Simple Circuit for Tracing Figures

crossed deflection fields, and a constant Wehnelt cylinder potential, using at the same time a phase-shift device as shown in Figs. 86 and 87. In Fig. 86 the sinusoidal voltage is in series with a resistance R and a condenser C whose values are such that the resistance of R is equal to the reactance of C. Thus across R and C are equal voltages, but with phase displacement of 90°. By applying these voltages to each pair of plates respectively the desired circular trace is obtained. The amplitudes of the deflecting voltage as well

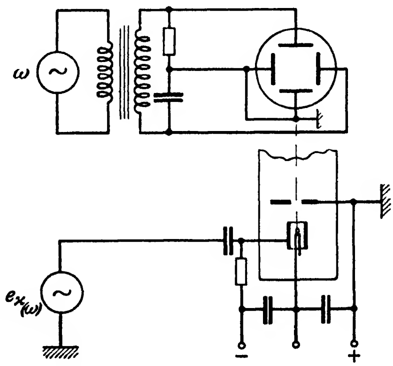


Fig 87 Tracing Circuit with One Side Earthed

as the radius of the circle amount to about 70 per cent spot deflection, which the alternating voltage itself would have given. The arrangement in Fig. 87 gives the amplitude as radius of the circle. It possesses the disadvantage of deflection

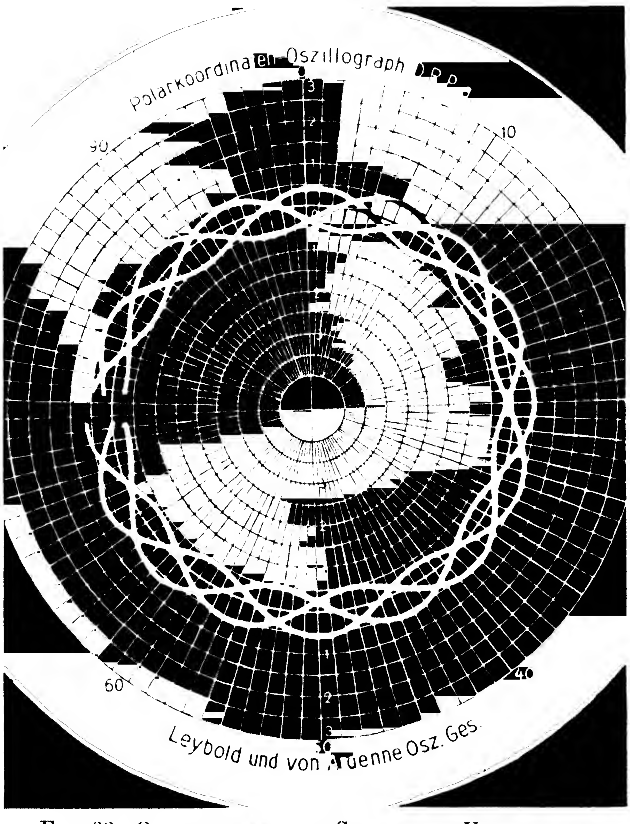


FIG. 88. OSCILLOGRAM OF A SINUSOIDAL VOLTAGE IN POLAR CO-ORDINATES

voltages which are not symmetrical to earth. The modulation of the vector amplitude has already been mentioned in the chapter on modulation, p. 55.

By superimposing the alternating voltage on the anode voltage the current is modulated and corresponding departures from the circular path appear on the oscillogram of the measured voltage.

As distinct from the method mentioned, in which the bridge arrangement for tracing the circle remains constant and the electron velocity is altered by the variable to be measured,

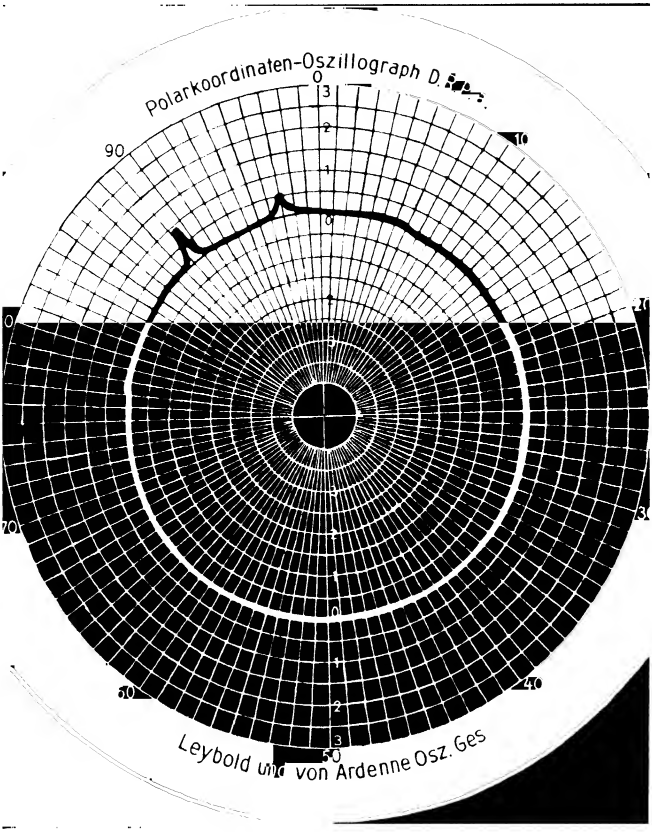


FIG. 89. OSCILLOGRAM OF TWO IMPULSES SEPARATED FROM ONE ANOTHER BY $7{\cdot}6 \times 10^{-6}$ SEC.

in the circuit of Fig. 90 the anode voltage is kept constant and the angular frequency across the bridge is varied by the voltage to be oscillographed. The particular advantage of this circuit can be seen from the fact that the whole oscillogram can be traced without altering the formation of the image, and with a spot of constant brightness. Deflection in polar co-ordinates by modulation has recently also been achieved by

others.[41] Goubau[42] arrived at the same conclusion, using a double push-pull arrangement. It must be remembered that a good circle can only be expected from high-vacuum tubes with a well-shaped sine wave from the source of voltage.[43]

Finally, it is possible to modulate the ray stream by the test voltage through the brightness control electrode, the bridge giving the circular time base being unaffected. This process is suitable only for phase measurement. It seems useless to attempt to measure the amplitude of the tested voltage by photometry of the spot on account of the inaccuracies of the screen itself. If it is required to ascertain the direction as well as the magnitude of the phase angle, a suitable stroboscopic method is that described by Hollmann and Saraga.[44] The velocity of the tracing spot appears to be reduced so much by the stroboscopic method, that it remains visible to the naked eye even when deflected at very high frequencies. This apparent reduction in speed by the stroboscope is carried out in a very simple way. The ray is modulated by an auxiliary frequency which differs slightly from the one under investigation. The modulation voltage can be superimposed on the control cylinder voltage or on the anode potential. Time marks which revolve in one direction or the other are then traced on the screen. If the modulation frequency is below the deflection frequency or its multiple then the stroboscopic motion of the time marks will be the same as the actual direction of the spot. The direction of revolution of Lissajou's figures can be detected in this way, and enables the phase deviation between the co-ordinates and a reversal of original sign to be recognized. Here are two examples. In the first case a series resonant circuit will act as an inductance or capacitance according as the applied voltage is higher or lower than that required for resonance. This can be demonstrated in Fig. 91 by comparing the phase of the resonant circuit LC with that of the voltage

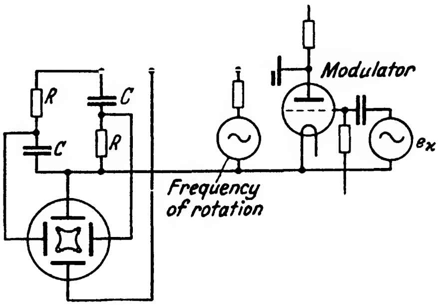


FIG. 90. MODULATION OF THE ROTATING VOLTAGE VECTOR BY THE VARIABLE UNDER EXAMINATION, THE ELECTRON VELOCITY BEING CONSTANT

across a pure ohmic resistance R. On the screen of the tube, a Lissajou figure appears above and below resonant frequency, the direction of rotation being reversed for leading or lagging

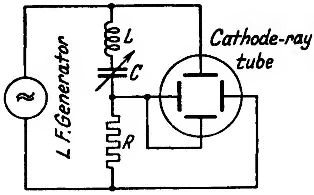


FIG. 91. STROBOSCOPIC EXAMINATION OF A COMPLEX RESISTANCE BY THE CATHODE-RAY TUBE

phase angles. An analogous experiment can, of course, be made with an oscillating circuit. In the second example, Fig. 92, the phase displacement of travelling waves can be examined by the method described. The phase angle φ between transmitter and receiver of a wave depends on their distance d apart

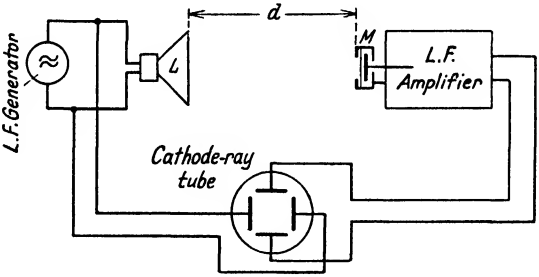


FIG. 92. STROBOSCOPIC EXAMINATION OF PHASE DISPLACEMENT OF SOUND WAVES

and the wave length λ, and is represented by $\varphi = \omega t$ where ω is the angular vector velocity and t the time. If the velocity of transmission $= v$, then $t = d/v$ and $\varphi = 2\pi d/\lambda$, i.e. the phase angle is a function of the distance d. This relation can be seen from the diagrammatic acoustic demonstration of Fig. 92, in which the exciting voltage for the loudspeaker L is applied to one pair of plates while the amplified voltage of the microphone M is applied to the other pair. By gradually increasing the distance between loudspeaker and microphone, the subsequent formation and disappearance of elliptical figures at intervals of half a wavelength with the corresponding reversal in direction of the rotating vector can be observed.

A very simple method of securing deflection in polar co-ordinates and one which is superior to all the methods previously described was developed by the author in 1936.* The operation is as follows: the cathode rays are deflected magnetically by a pair of coils forming part of an oscillatory circuit. The corresponding pair of plates is connected to a condenser in the circuit so that a circular deflection is produced since there is always a phase angle of 90° between the current and the voltage in an oscillatory circuit. The design is such that a symmetrical deflecting voltage results and produces an excellent tracing. The variable under examination is impressed on the second deflecting system which consists of a pair of coaxial cones. The frequency range covered is from 600 to $2 \cdot 10^5$ cycles. Usually a frequency of 10^4 is employed and it may be synchronized by a quartz operated transmitter if desired. The precision of measurement is about 0·5 per cent, which corresponds to $2{\cdot}5, \times 10^{-8}$ sec. at a frequency of 2×10^5.

An oscillogram recorded from a sinusoidal voltage is shown in Fig. 88, and Fig. 89 indicates two short impulses following one another in quick succession. If higher tracing speeds are required, a saw tooth oscillation may be fed to the deflecting cone forming a "time spiral," which allows the time base to be extended considerably.

Wherever precise measurements involving very small time intervals are involved, the Polar co-ordinate electron oscillograph, developed by the author along the lines indicated, is recommended.

4. **The Effect of the Time of Transit of the Electrons in High-frequency Work.** (A) ELECTROSTATIC DEFLECTION. Errors occur in the tracing of very high frequencies as a result of the fact that even the cathode stream is not entirely devoid of inertia, since the electrons move through the deflecting field with finite velocity. If the time during which the electrons are in this field is large compared with the period of alternation of the field, then there is a reduction in sensitivity and a phase error occurs when the frequency is high. This is what happens in the case of oscillographs with low anode voltage, i.e. low ray velocity and long deflectional fields.

(i) *The Dynamic Sensitivity of the Tube at very High*

* M. von Ardenne, "Ein neuer Polar-Koordinaten-Elektronenstrahl-Oszillograph mit linearem Zeitmasstab. *Zeit. f. tech Phys.* Vol. 17 (1936), p. 660.

Frequencies.[45] The equation (26) already given is valid only as long as the deflecting field is constant during the passage of the electrons through it. On the other hand, if the period of the deflecting field is comparable to the time taken by the electrons, then the former is not constant during this time. The resulting conditions can be explained by the aid of Fig. 93. An electron comes between the deflection plates at the precise moment when the instantaneous value of the deflecting voltage is zero. The voltage changes as the electron passes on, going through its positive half-cycle first and then its negative half. The distribution of voltage in space is shown above the upper deflecting plate.

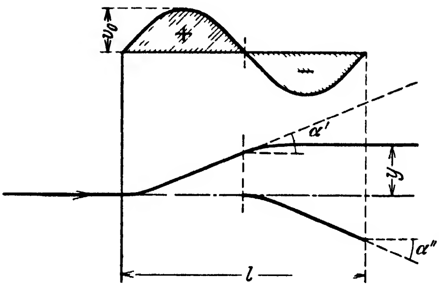


FIG. 93. PATH OF AN ELECTRON IN A HIGH-FREQUENCY DEFLECTING FIELD WHEN THE TIME OF PASSAGE IS EQUAL TO THE PERIOD OF THE FIELD

If only the positive half of the wave is considered, it will be seen that this produces a deflection through an angle α' so that the electron would continue its flight along the dotted line. Also the negative half-wave deflects the electron in the opposite direction through an equal angle α''. If the electron traverses both half-waves successively then after a complete period the angular deflection α' is completely cancelled by the deflection in the opposite direction, and the electron continues in its original direction. The parallel displacement y compared with the screen deflection A can be ignored.

Further, the diagram shows that the deflection is greatest when the time of transit corresponds to exactly one-half period. The cathode-ray tube therefore fails completely when the traverse time corresponds to the time of one cycle. On the other hand, when it equals one-half period there is a point of maximum sensitivity.

The mathematical formula for the above is obtained from the following considerations. If the electrons had the velocity of light, then the length of a complete period, as assumed in the discussion of the voltage distribution along the deflecting

plates, would equal a whole wavelength λ. As, however, the electrons move at a lower velocity v_c, the voltage distribution along the deflecting plates would appear to be shortened to the extent v_0/c. As the explanation is similar for more than one period, it will be appreciated that the cathode-ray tube becomes quite insensitive when the length l of the deflecting plates is exactly equal to the corrected wavelength, i.e. when

$$l_0 = n\lambda(v_0/c) \text{ (where } n = 1, 2, 3 \ldots) \quad (34a)$$

A very strong deflection is obtained whenever the length of the plate is equal to one-half wavelength (corrected), so that maxima in sensitivity are obtained when the length l amounts to a corrected half-wavelength or an odd multiple of it, i.e.

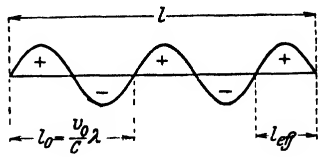


FIG. 94. EFFECTIVE LENGTH OF PLATE AND REDUCED WAVE-LENGTH

$$l_{max} = (2n - 1)(\lambda/2)(v_0/c) \quad (34b)$$

If the frequency is so high that several corrected wavelengths are spread along the deflecting plate, then each pair of half-wavelengths cancel one another. There is only a small effective portion, and the effective plate length as given in Fig. 94 becomes $(\lambda/2)(v_0/c)$ maximum. But since according to equation (19) the sensitivity decreases with shorter length of plate, it follows that the dynamic sensitivity must be less for this reason.

The exact mathematical treatment of the problem is given in the relation for the transverse acceleration

$$g = (e/m_0)(v_p/d) \sin(\omega t + \omega t_1) \quad . \quad (35)$$

where t indicates the time variable in the accelerating field and $t_1 = \frac{x}{v_0}$, its space distribution with respect to the moving electrons. From this, the value of the dynamic sensitivity ignoring its phase relation is obtained as

$$a_\omega = a_0 \frac{\sin(\phi/2)}{\phi/2} \quad . \quad . \quad . \quad . \quad . \quad (36)$$

where φ is the phase angle, ω the angular vector velocity, and the electron traversing time t_1 is given by $\varphi = \omega t_1$.

In Fig. 95 the deviation of the ray is given as a function of the frequency for a plate of length 2 cm. and anode voltage

1 000. At the points corresponding to equation (34a) the sensitivity of the tube is zero, whilst at the frequencies given by equation (34b) it is a maximum, the ordinates of which decrease as the frequencies increase. If the anode voltage, i.e. the electron velocity, is altered, the whole curve is displaced so that adjustment to a maximum sensitivity can always be made. The sensitivity does not always increase with decreasing anode voltage if the null point is being approached or has just been passed, or as in the case of static sensitivity indicated by

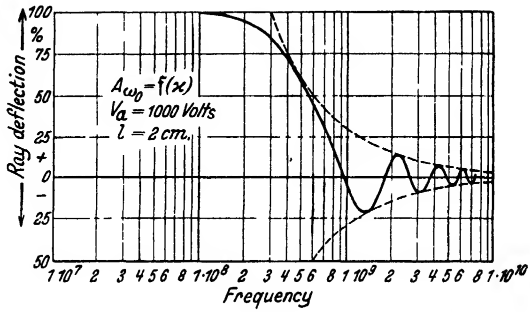


FIG. 95. SENSITIVITY OF THE CATHODE-RAY TUBE AS A FUNCTION OF THE FREQUENCY

equation (26). It may just as likely decrease. This will be shown later by experiment.

(ii) *Phase Displacement between the Co-ordinates.* By arranging the pairs of deflection plates, which are perpendicular to one another, behind one another, an additional phase displacement between the voltages applied to the deflecting plates occurs. E. H. Hollmann was the first to investigate this thoroughly. As the electrons require a finite time to pass from one pair of plates to the other, a time lag in both co-ordinates occurs between the deflections amounting to

$$\tau = d/v_0 \quad . \quad . \quad . \quad . \quad . \quad (37)$$

or expressed as a phase angle

$$\psi = \omega\tau = \omega d/v_0 \quad . \quad . \quad . \quad (38)$$

If alternating voltages in phase are applied to both deflecting systems, the screen of the tube registers a straight line inclined at 45° to the deflecting systems. If now a phase displacement

between the deflecting plates occurs, the straight line will be drawn out to an ellipse or a circle. At very high frequencies there will be a phase displacement due to the angle ψ between the two deflecting systems in the tube itself, so that deflecting voltages in phase with one another will not produce a straight line. It is only when the phase displacement—proportional to $\sin \psi$—becomes zero that the tube is suitable for investigating

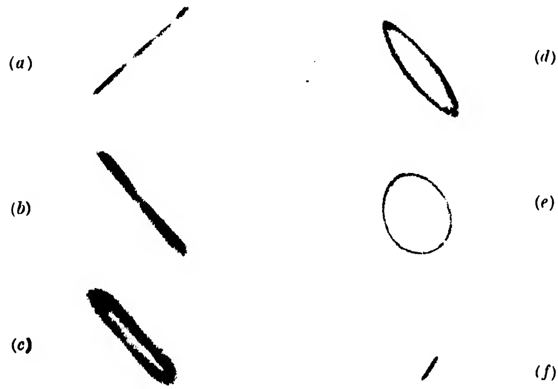


FIG. 96. STATIC CHARACTERISTIC AND INVERSIONS DUE TO THE EFFECT OF THE TRAVERSE TIME OF THE ELECTRONS

high frequencies. This condition is always fulfilled when ψ is a multiple of 180°. That is,

$$\psi = \omega d / v_0 = n\pi \quad . \quad . \quad . \quad (39)$$

therefore indicates freedom from internal phase distortion.

Certain ray velocities v_0, or corresponding anode voltages, satisfy this relation and in consequence produce a straight line on the screen, whilst other values result in circular figures.

In Fig. 96 various deflection traces are shown which, with the exception of (*a*) taken at 50 cyc., were obtained with a wavelength of 84 cm. All the oscillograms were taken with plate systems directly coupled, i.e. in phase. Fig. 96 (*a*) shows the static orientation of the co-ordinates with a 50-cycle deflecting voltage. At 1 200 volts and wavelength 84 cm. the straight line of Fig. 96 (*b*) is obtained, and this, compared with

the static characteristic of Fig. 96 (*a*), is rotated through 90°. At an anode voltage of 1 500 volts it can be seen (Fig. 96 (*c*)) that the straight line splits up as the anode potential rises, and that at very high potentials it reverts to the static characteristic of Fig. 96 (*a*).

Figs. 96 (*d*), (*e*), and (*f*) represent lower potentials, and it can be seen how the dynamic characteristic of (*b*) alters from an ellipse at 800 volts (*d*) to a circle at 550 volts (*e*), and reverts at 230 volts (*f*) to a straight line. Now this characteristic of photograph (*f*) has the same orientation as the static characteristic, and represents a characteristic of the second order in which the time of passage of the electron between the two plates has produced a phase change of 360°. At the same time, the decrease in sensitivity as the anode voltage rises can be seen at once from the photographs of the smaller tracings. The tube is therefore operating on a falling portion of the sensitivity as explained in the last section. In this instance. the first zero point is implied, this being reached at an anode voltage of 2 000. Phase displacement between the co-ordinates makes analysis of oscillograph images difficult at very high frequencies. The method of phase correction by suitable adjustment of the anode voltage, which will have to be made for each frequency in a given tube, is an objectionable complication in practice. Consequently it is advisable to carry out phase correction independently of the anode voltage. Hollmann[46] evolved a special arrangement of the deflection plates for doing this, as shown diagrammatically in Fig. 97. The new plate system differs from the original by the fact that one of the pairs of plates P_2 is divided into two equal parts which are placed at equal distance d' and d'' on either side of the other pair of plates P_1. When the section d' is traversed, a phase displacement occurs, the angle being $\psi' = \omega d'/v_0$. The section d'' is traversed in the opposite direction, and thus causes a phase displacement $\psi'' = - \omega d''/v_0 = - \psi'$. The resultant phase displacement is therefore zero, so that the tube is free from phase error at all frequencies and electron velocities.

In short, it may be said that the efficiency of the tube for high-frequency electrostatic deflection is limited by the sensitivity required, and this in turn is fixed by the form of the field l/a. The smallest distance a is limited by the radius of the stream which, in order to avoid disturbance, by electron reflection and diffusion, must not approach the plates by a

distance less than twice its diameter. The length of the plates cannot be increased at will on account of constructional difficulties, and in any case such a change is not an efficient arrangement at high frequencies since the dynamic sensitivity is controlled by the effective plate length. A further limit to the operating capacity of the tube is set by the electrode resonance, which in turn is determined by the ratio of capacitance and inductance of the plate circuit. The resonant frequency of the plate circuit for most tubes corresponds to a wavelength of a few decimetres, a region in which the tube is hardly suitable for use.

(B) MAGNETIC DEFLECTION. In cases where the time involved is not long compared with the traverse time of the electrons, the considerations of frequency occur in magnetic just as with electrostatic deflection. However, with magnetic deflection the region of very high frequencies will seldom be reached since coils designed for adequate sensitivity would be of too high impedance. Limitations due to frequency are reached in the external circuit before they become of importance in the tube itself.

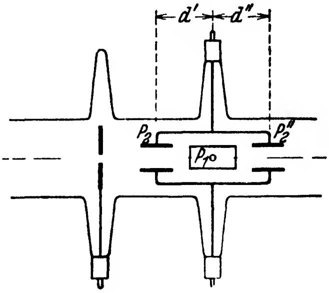


FIG. 97. SET OF DEFLECTING PLATES FOR VERY HIGH FREQUENCIES

V. TUBE CONSTRUCTION

The general theoretical fundamental principles, a knowledge of which is essential for the practical development of cathode-ray tubes for work involving small currents, have been considered in the previous sections. The following sections will give first of all directions for the construction and assembly of such tubes. The maximum efficiency of the tubes will be attained only when each component is developed to suit its own particular purpose.

1. **Component Parts.** The component parts of the tube for low voltage use consist of the cathode, the focusing element, the deflecting system and the glass tube with its fluorescent screen.

(A) CATHODE AND PRE-FOCUSING. The efficiency of the tube depends to a great extent on the efficiency of the built-in

cathode which, for reasons explained in the earlier sections, functions as a hot cathode for low voltage work.

(i) *Fundamentals of Electron Emission.* The emission of electrons from hot metals is analogous to the evaporation of a liquid: Forces acting on the electrons in the interior of the metal and at the surface restrain them from passing into the surrounding space. The work necessary to eject the electron from the metal to the surrounding space across the surface is called the *work function*, and corresponds to the latent heat of vaporization of a liquid. It is supplied by increasing the kinetic energy of the electron by raising the temperature. The relation between the number of electrons emitted and the temperature, or between saturation current of the hot cathode and the temperature, is given by Richardson's equation

$$I_s = q_0 E T^2 e^{\; e\varphi/KT} \quad . \quad . \quad . \quad (40)$$

where q_0 is the effective cathode surface, E a universal constant deduced from theoretical considerations and having a value 60·2 A./cm.^{2} deg.^{2}, $e = 4{\cdot}77 \times 10^7$ e.s.u. the elemental charge, $K = 1{\cdot}36 \,.\, 10^{-16}$ erg./deg., the molecular gas constant, T absolute temperature, and φ the work function in volts.

The equation shows that the cathode stream is very small at low temperatures, increases considerably from a certain temperature upwards, and finally obeys an exponential law almost exactly. The effect of temperature in gas-filled tubes is of great importance, since the initial concentration and main gas-focusing start with a certain emission. Further, the Richardson equation shows that for a constant temperature the smaller the work function the greater the emission current. The work function is a constant of the material itself. Experiments have proved that E is not a constant but is dependent within wide limits on φ, and therefore on the material of the cathode. This result shows what a fundamental influence the choice of suitable material for the cathode has on the efficiency of the tube. The electrons near the hot cathode are conducted away through the influence of the field due to the potential difference between the cathode and the accelerating electrode. The greater the anode voltage and the penetrance of the anode on the emitting cathode surface, the more closely will the electron stream approximate to a saturation current from the cathode.

(ii) ***Requirements of a Hot Cathode.*** The requirements of the

hot cathode of a cathode-ray tube differ from those of an amplifying valve owing to the special purpose for which such tubes are designed. It is important not only to increase the total emission as much as possible, as in the case of the amplifying valve, but even more so to ensure that the density of the electron stream is as great as possible. The diameter of the beam, and therefore of the cathode, should be as small as possible. A high-specific emission is essential because the sharpness and brilliancy of the spot on the fluorescence screen, and therefore the efficiency of the tube, are determined by the initial cross-section and magnitude of the beam. According to the Richardson equation, a high-specific emission cannot be obtained by merely increasing the temperature as desired. The equation shows that emission depends not only on temperature but on the value of E. Theoretically the desired emission can be obtained by a corresponding increase in temperature when E falls below a certain minimum, but the overloading of the cathode which results reduces its life considerably, or else the cathode burns out before the desired emission is reached. For instance, it is scarcely possible with gas-focusing to get the necessary specific emission with a useful life from a pure tungsten filament. Even if the necessary specific emission could be obtained by increasing the temperature without burning out the cathode, this method of control would be disadvantageous. The high heating currents required would necessitate leading-in wires which would be diffiult to seal to the glass. Again, the magnetic field near the cathode would become so strong that disturbances would occur with the use of alternating current even if special cathode construction—to which reference will be made later—were adopted. In addition, the use of a high-cathode temperature is extremely undesirable, because as a source of light it would illuminate the screen. The illumination of the screen by the cathode can only be eliminated by means of various additional, and to some extent troublesome, modifications in construction, which all use one principle—that of making the cathode invisible when viewed from the screen. In order that the electrons may pass the light trap in the circuit, additional electrostatic or magnetic fields must be created.

To secure high specific emission, which to a large extent helps to determine the efficiency of the gas-filled as well as the high-vacuum type, the zone of the cathode which contributes

to the source of rays should be made of regular emissivity. With the reduced gas pressure type, and even more so with the high-vacuum type, it is possible to secure an enlarged electron image of the cathode visible on the screen. To do this it is only necessary to make the voltages of the lens electrodes slightly different from those used for normal operation, where the electron-optical system is so adjusted that the enlargement obtained is a minimum. By electron-microscopic observation,

FIG. 98. OXIDE CATHODE ABOUT 0·3 MM. DIAMETER
At the beginning of the forming process (*left*); after the process has been in operation (*right*)

not only the forming process during pumping but also the changes in distribution of emission of the cathode tubes can be followed, and can be examined as the number of hours of working increase. Local disturbances, due to ionic bombardment, or disintegration of the oxide during extended periods of operation and high specific loading, can be observed. Two illustrations which show the start and later on the progress in forming a cathode of small cross-section for a reduced gas pressure tube are reproduced in Fig. 98. Fig. 99 illustrates a similar cathode in which the oxide is placed in a fine round hole in a nickel carrier. The crystal structure of the nickel is also very clearly shown in the photograph. For more extensive cathode examination it is advisable to use special electron-optical systems, known as electron microscopes, which were described some years ago. [47] [48]

In constructions in which the cathode is formed as an image on the screen directly, the examination of the emission distribution over the cathode is of particular interest, as this determines the brightness of the fluorescent spot. In gas-filled tubes the

electron-optical image is often considerably disturbed by striation and diffusion of the electrons. If the distribution of emission in gas-filled tubes is to be investigated by electron-optical means, the cathode should only be slightly heated so that no gas-focusing occurs, even at the strongest emissive centre.

The life of the hot cathode depends in the case of the vacuum tube only on the specific loading. In gas-filled cathode-ray tubes it is also influenced by the following facts. The + ions moving towards the cathode under the influence of the anode field rapidly destroy the film of oxide on the cathode by ionic bombardment, unless special electrostatic or mechanical adjustments have been made to deflect these ions away from the filament. The destructive effect on the + ions depends on their kinetic energy, and therefore on the applied voltage. From experimental evidence gas-filling appears to influence the cathode evaporation, which is greater with gases of high than with those of low atomic weight. The microphotographs of Fig. 100 give an impression of the intense mechanical disturbances caused by ionic bombardment. On the left can be seen a fresh cathode in which the oxide is placed in a drilled hole, the depth of which is about equal to its diameter. This is the same cathode which is reproduced by the electron microscope above to demonstrate its progressive formation. On the right of the photograph is seen the appearance of an old cathode which has been burning several hundred hours. The oxide, as well as the indirectly heated carrier, have been considerably pitted. By considering this and similar microphotographs, it is obvious that the life of the gas-filled type depends to a great extent on the effective reserve of oxide and its consistency. For a given cathode, the life will be greater the less the gas pressure, the weaker the ray current and accelerating field in front of the

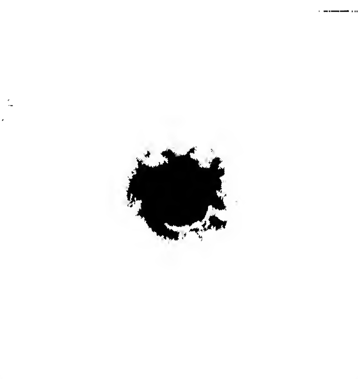


FIG. 99. ELECTRON IMAGE OF AN INDIRECTLY HEATED HOLE CATHODE ON A NICKEL CARRIER

Magnification about forty times

cathode, and the smaller the impact factor of the oxide for the ions formed. The reduction of the pressure necessary for gas-focusing to the order of one-tenth, due to improvement in focusing by electron-optical means, has resulted in an increase in life of the tube by about 10 times compared with the older types.

(iii) *Production of the Hot Cathode.* The production of the hot cathode for gas-filled tubes must be carried out with the fore-

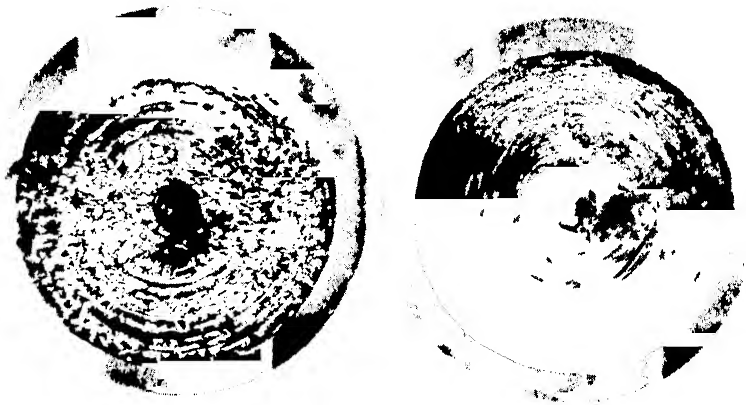


FIG. 100. MICROPHOTOGRAPH OF A NEW (*left*) CATHODE AND ONE OF AN OLD GAS-FILLED TUBE WHICH HAS BURNED SEVERAL HUNDRED HOURS (*right*)

going considerations in mind—high specific emission, small emissive surface and low work function of the material in question. Selection of the three fundamental components of the hot cathode—the supports, active mass of oxide, and medium for holding the oxide in suspension—must be similarly considered.

Rather varied considerations determine the choice of the oxide carrier, according to whether a simple wire cathode, which nowadays would probably only be made in the laboratory occasionally, or a more massive indirectly heated cathode is to be used. Chrome-nickel, platinum, iridium, and platinum-iridium are suitable materials for the core of the wire cathode, while metals of still higher melting point such as tungsten are

less useful. The substances mentioned are malleable in the form of wire, show no signs of serious brittleness even when bent, and remain sufficiently rigid in a heated condition. Nickel and nickel alloys are used almost exclusively for carriers for indirectly-heated cathodes. In principle only vacuum-furnaced carrier material should be used, in order to keep the gas occlusion of the cathode as small as possible and to shorten the pumping schedule. Lastly, an emission of gas from the carrier substance will affect the emissivity of the oxide and reduce the life.

The selection of suitable oxide material is of vital importance to the efficiency of the cathode. Two principal methods of production are in use—the coating or pasting process, and the fusion process. The first is the older, though even to-day it is the most suitable for cathode-ray tubes and is the one most generally used. Carbonates, hydrates, nitrates, hydroxides, peroxides, and oxides are mainly used as bases. The oxides have the disadvantage of being less stable in air, and after a comparatively short time are finally converted into hydroxides or carbonates.

The compounds, as finely divided as possible, are mixed with paraffin oil, melted paraffin, or resin into a paste. This is preferably carried out in a ball mill or mortar. The paste should be ground in the mill from 24 to 48 hours in order to make the particles as small as possible. The paste is then allowed to stand for some time for the heavy particles to settle, and only the upper layer is used in the production of the oxide cathode. The paste is applied to the core wire, the surface of which has been cleaned by heat and chemical treatment. The next process is to drive off the paraffin oil by evaporation, by heating the wire slightly in an oven or passing an electric current through it (300°-500° C.). Then, by heating to a red glow (about 1 000° C.), the substance on the core becomes firmly fused together and at the same time is converted to an oxide, or in the presence of CO_2, a carbonate. This process is repeated until the film of oxide is sufficiently thick and the core wire completely coated.

The second process consists in using substances soluble in water, i.e. nitrate or hydroxide. Difficulty arises chiefly when the oxide carrier has traces of impurities on its surface or has an irregular surface, in which case it does not receive an even coating. The first application results in a very thin film so

that the paste must be applied repeatedly in thin coatings before the filament has a sufficiently thick covering. Instead of dissolving the nitrates, the wire can be immersed in the fused nitrates or the glowing wire can be touched with a nitrate crystal. Generally, it appears preferable to immerse the nitrate or hydroxide in paraffin oil. This is technically termed the *fusion process*. Alcoholic solutions of the oxides are also used.

With hot cathodes for gas-filled cathode-ray tubes, care must generally be taken that only the apex facing the anode or a nearly circular surface with a diameter generally less than 0·5 mm., or a boring of similar size is covered or filled with oxide, as otherwise an undesirably large ray cross-section or deformation of the ray will occur. For gas-filled tubes, therefore, water pastes are more suitable than oil pastes, as the latter tend to cover the entire surface of the oxide carrier immediately, even when only small quantities are applied. In contrast to this, in high-vacuum tubes a greater surface of the oxide carrier is almost always evenly covered with oxide, for instance, by spraying; and later by arrangement, formation and bias of the brightness control grid it is ensured that only a relatively small zone of the oxide covered takes part in the emission. By this process, it is possible to secure very evenly emitting surfaces in high-vacuum tubes. Even in high-vacuum tubes a certain reserve of oxide is necessary. The thickness of the oxide layer on the carrier must not therefore be too small. Too thick a layer is undesirable as difficulties of forming and de-gassing result.

After applying the active material and fitting the cathode in the tube, the residual gas in the oxide mass and in the support wires must be removed by heating. The cathode is consequently heated slowly while the tube is on the pump, up to a temperature of about 1 050° C. It is advisable to control the temperature by pyrometers, and care should be taken to observe the actual filament temperature at the point at which the emission will eventually take place. Heating should be continued until the vacuum gauge indicates a pressure which is certainly not greater than 10^{-6} mm. Hg., and is maintained when the pump has been disconnected for some time. The actual activation of the cathode—so-called "forming"—takes place immediately after the heating process.

A voltage having an initial value of 30-500V according to the value of D, is applied between the first accelerating electrode

and the cathode at the operating temperature of the cathode (850° C. for paste cathodes), the Wehnelt cylinder being either out of circuit or connected to the cathode. This voltage is raised slowly to a final value of 200–3 000 volts according to the type of tube, the gases set free during the forming process being pumped off simultaneously.

It will be observed during this operation that the emission rises slowly to an appropriate maximum for each voltage which must be periodically adjusted. Only then must the voltage be further increased, i.e. when this emission value is reached. It is of the greatest importance to see that a glow discharge, which may result from high forming voltages and the liberation of large amounts of gas, does not pass into the tube during the forming process, as this would result in the immediate destruction of the oxide mass. Forming is completed when the specific emission reaches 1 mA./mm.^{2} of the effective cathode surface.

At the same time as the oxide is gradually consumed as a result of the high specific load at the point of emission, a slight trace of oxygen can be observed. It is advisable, therefore, as in the case of valves, to use getters such as barium or magnesium in cathode-ray tubes, since they remain chemically active in spite of the oxygen.

The release of hydrogen is sometimes observed, and is best counteracted by extending the furnacing treatment and the pumping period.

Further details of activating substances and methods are to be found in *Handbuch der Experimentalphysik*, Vol. 13, 2, in the section "Production of Hot Electrodes" (Simon, H.).

(iv) *Construction of Cathode and Prefocusing Electrode Assembly.* Numerous ideas for dimensions, shape and geometrical arrangement of the cathode in the electrode system have been published and are more or less useful according to the purpose to which the cathode is to be applied, the method of operating it and material available for construction. Types of cathode construction fall into two groups—those which can only be heated by direct current (usually from an accumulator) and those which permit of heating by alternating current without causing a disturbance of the rays by the magnetic field surrounding the cathode. All cathodes developed for heating by a.c. supply are not ideally suitable for heating from d.c., since the high consumption—not material where direct supply mains are

available—is an important consideration if the supply is taken from a battery, since it is particularly desirable that the operating voltage shall be constant over long periods.

It is only recently that the a.c. cathode has been brought to such a state of perfection that it can be operated without causing other disturbances, and only consumes a small power (< 2 watts). These cathodes soon became general, and are employed with very little variation in all modern forms of tube construction.

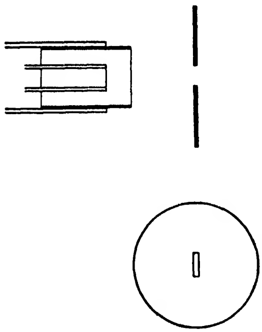


FIG. 101. OLD TYPE OF CATHODE FILAMENT FOR PRODUCING LINE IMAGES

Nevertheless, we will not in this section omit a description of the older forms of cathode which are no longer used, as the older types particularly are more easily built up for simple laboratory experiments than the improved and more recent forms.

(v) *Direct Current Cathodes.* The most obvious form of construction similar to that of the amplifying valve, is the simple straight filament which is drawn out at right angles to the axis of the tube and fixed at both ends. Such a cathode is shown in Fig. 101 inside a Wehnelt cylinder. The filament must be made very short in order to obtain fairly sharp fluorescent images. In consequence, the filament current has to be considerably increased on account of the cooling at the support. If the filament is short enough, only the central portion attains the temperature necessary for emission, since heat is conducted away at its extremities. It is an advantage for the forming process to be carried out in such a way that only the centre of the filament is activated. This type of hot cathode is not particularly suitable for sharp fluorescent spots, but it used to be an important one if the production of line images such as occur with sound-film tubes were required. A type of cathode suitable for point images is that shown diagrammatically in Fig. 102, the so-called *Wehnelt cathode*. The filament is replaced by a band about 2 mm. wide, in the centre of which a small indentation about 0.5 mm. dia. for holding the mass of oxide is made by means of a centre punch. A source of emission approximating to a point is obtained without difficulty when the cathode is formed in the shape of a hairpin (Fig. 103). During the process of activation care must be taken to see

that only the top of the hairpin which faces the anode becomes coated with oxide. Fig. 104 shows a combination of the hairpin and small cup-shaped cathodes.

In the case of various d.c. or a.c. cathodes discussed in this

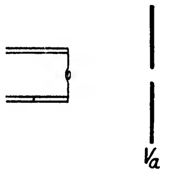


FIG. 102. CUP SHAPED CATHODE (*Wehnelt*)

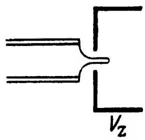


FIG. 103. HAIR PIN CATHODE

chapter, the oxide is applied to more or less definite points. These "point" cathodes which were employed almost exclusively in the older gas-filled tubes, possess the advantage that the + ions produced do not, in consequence of their inertia, follow the sharp bends in the lines of force of the field near

FIG. 104. CATHODE WITH OXIDE CUP ON PLATINUM STRIP AS A PROLIFIC SOURCE OF EMISSION (*O. Pressler*)

the point, but fly past it. The oxide impact factor is relatively low with point cathodes, so that even at higher gas pressures satisfactory life can be obtained. If the oxide of a point cathode is carried by a wire, the wire should be sufficiently strong as otherwise there is a danger that it may become reduced in strength by evaporation and burning through, before the consumption of the emissive oxide layer has

proceeded too far. For gas-filled tubes without an accelerating lens the configuration of the field near the point is an advantage also with regard to the focusing effect. In gas-filled tubes of modern construction as well as for all high-vacuum tubes where the cathode surface is formed as an image on the screen, the point cathode is disadvantageous from an electron-optical point of view, and is best replaced by an equipotential surface cathode. In high-vacuum systems where the smallest possible ray section does not coincide with that at the cathode surface, point cathodes, sometimes surrounded by a small Wehnelt cylinder similar to Fig. 103, are sometimes used as an electron source. An equipotential surface cathode which suffices for simple experiments can be improvised by welding a small nickel plate on the filament (Fig. 105). In this way an equipotential cathode is obtained since the small plate is heated by the hot filament, so that there is practically no voltage drop across it. This cathode, according to Ende,(49) is only suitable for the production of filament rays when a specially shaped aperture is fitted which, according to Brüche, also focuses the electrons by reflecting them from negative charges on the walls.

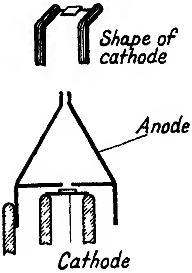


FIG. 105. OLD FORM OF EQUIPOTENTIAL CATHODE (W. Ende)

At the same time the hat-shaped anode provides a mechanical protection of the hot cathode against approaching ions. The principle of mechanical protection against electron concentration was first applied in a small tube arrangement produced by van der Bijl(50) and Johnson,(51) but an ordinary aperture was arranged between the cathode and the small tube. This electrode system for cathode-ray tubes was taken from the principle applied by Lilienfeld(52) for hot cathode Röntgen tubes. According to this principle the anode field does not penetrate to the surface of the cathode, but only to the cloud of electrons which surround the hot wire cathode, the latter serving solely as the source of electrons. The electrode system used by Johnson is shown in Fig. 106. Naturally the diameter of the circular cathode is greater than that of the hole, so that the anode potential is effective only on that part of the space charge which is inside the cathode ring. Gas ions which penetrate the aperture in spite of the mechanical protection do

not hit the activated oxide on the inner side of the ring, but go right through the cathode ring. The given oxide impact factor for the ions can, according to the observed average life, be hardly smaller for these arrangements than for the simpler

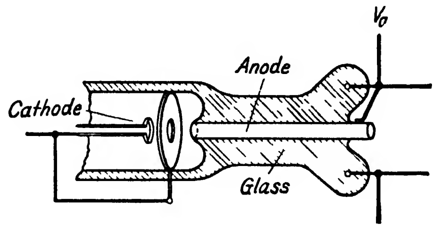


FIG. 106. ELECTRODE ARRANGEMENT FOR REDUCING ION IMPACT ON THE CATHODE (*Johnson*)

one with point cathode and Wehnelt cylinder. The electrode arrangement of Sommerfeld[53] is shown in Fig. 107, and operates in the same way as the Lilienfeld contrivance.

The small protecting tube at anode potential is conical shaped in accordance with the ideas of Rogowski[54] and Grosser,

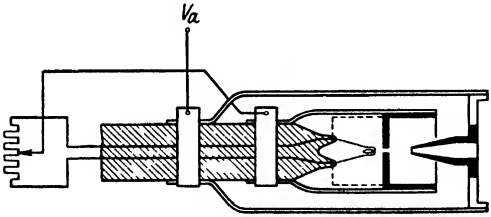


FIG. 107. ELECTRODE ARRANGEMENT (*Sommerfeld*)

and projects into the anode side of the cylindrical extension of the cathode window, so that by this means an additional electrostatic focusing of the electron stream can be secured.

(vi) *A.C. Cathodes.* Heating of the cathode by direct current has various drawbacks. With battery operation, recourse must be made to adjustment of the resistance in series as the battery runs down, since this is practically the only method of control. After the battery has been almost completely discharged and the heater current switched off, damage may be done to the filament when the battery is switched on again unless in the meantime the rheostat has been adjusted, since the battery recovers in the interim and its terminal voltage is higher than

when disconnected. The cathode may also be damaged by underrunning, which will take place to a slight extent as the battery discharges. Under these conditions, the cathode voltage drop becomes greater and ionic bombardment increases, causing rapid disintegration. The charging and servicing of batteries for d.c. heating are also troublesome. D.c. operation makes it difficult to meet the requirement of controlling the whole oscillograph set simply and effectively by means of a single switch. Not the least disadvantage is the fact that the batteries or other source of cathode current are almost always at a high potential corresponding to the full anode voltage. Frequently difficulties of mounting and unavoidable leakage occur, so that elaborate precautions become necessary particularly with installations operated under other than laboratory conditions. The difficulties described do not occur with a.c. operation or at any rate do so to only a very small extent. As distinct from the well-known conditions which occur with amplifying valves, it was not essential for the cathode of the old gas-filled tube to be an equipotential surface. The control voltages of the tube of the old gas-filled type are high, and the drop at the cathode is very small in almost all forms of construction, so that the latter factor can be ignored. In addition, since the effective length of the cathode is nearly always small compared with its total length, there is, in most cases only a fraction of the total voltage at the actual point of emission. Actually, therefore, the equipotential cathode is the one in most general use. The real problem of the a.c. cathode for these systems lies in the production of types in which the heating current produces no magnetic field in the path of the ray. In a number of cathode constructions, the problem has been solved and the most important of these are discussed below.

The disturbing effect of the magnetic field due to the heater current increases with the current, and is greater for lower electron velocities or anode voltages. In tubes developed primarily for use with low anode voltages, only cathodes in which the heating current is low (approximately 1 ampere or less) would seem suitable for a.c. operation, since the stray fields due to the heating conductors cause appreciable ray deflection. Cathodes with higher values of heating current can only be used when the field created by the heated conductor is neutralized by criss-crossing the wires.

A type of directly-heated cathode which has proved particularly effective in practice is the one with a compensated magnetic field, devised by H. von Hartel.[55]

Various suggestions for forming the cathode are given in Fig. 108. One construction of practical use is that in which the filament is looped into the shape of a figure eight, open at the lower end. All cathodes are constructed so that the field due to the more remote current paths neutralizes the magnetic field in the region of the point of emission. In practice it is important to ensure that an a.c. field of the smallest possible

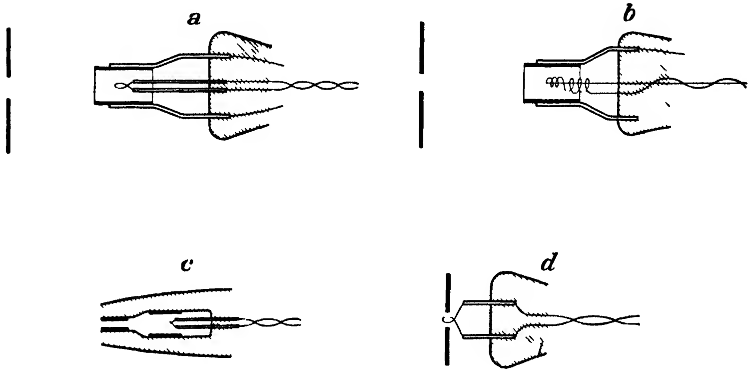


FIG. 108. OLD FORM OF WIRE CATHODE FOR A.C. OR D.C. HEATING. NEUTRALIZATION OF THE MAGNETIC FIELD DUE TO THE FILAMENT
(*H. von Hartel*)

magnitude exists at or near the point where the electrons have their lowest velocity, in the region of lowest potential. Where a Wehnelt cylinder is used the region of lowest potential is near the opening to the interior of the cylinder.

Fig. 109 shows the construction of a looped cathode of an old type in which the Wehnelt cylinder is split open for the purpose of illustration. The optimum dimensions once ascertained can be reproduced consistently with suitable methods of production, and the control voltages applied from time to time have so little influence on the compensation conditions that it is not generally necessary to correct errors of compensation by special leads for the heating conductors outside the tube. The cathode of the type shown in the photograph uses no more current, on account of direct heating, than the wire

cathode previously described and this can, of course, be done by d.c. without any special devices.

The simple loop cathode has the disadvantage that the emissive point can easily assume larger dimensions than are desirable when the oxide is applied. The type shown in Fig. 110, to the loop of which a short piece of wire is welded, has much greater advantages in this respect. The piece of wire carries the oxide and is heated by conduction from the loop. A suitable emissive surface of small dimensions is obtained from a filament the substance of which is one which is quickly de-activated (e.g. tungsten), and where the welded point consists of a suitable carrier material such as platinum. The difference in the sharpness of the spot with the normal loop cathode and the point cathode is shown in Fig. 111 (*a*) and (*b*). The sharper tracing on the left was obtained from a point cathode, while the one on the right, which is more blurred, was made by a well-shaped loop cathode. One disadvantage of the point cathode of Fig. 110 is that the heating wire is easily weakened by welding, and is apt to burn out at this point later. Another disadvantage is that a low temperature exists at the point of the wire where the emission is required in consequence of the fall in temperature which occurs along the wire. It is quite possible, therefore, for that part of the wire farthest from the anode to emit more profusely than the portion facing the anode, so that

FIG. 109. ARRANGEMENT OF UNIVERSAL TYPE OF CATHODE IN THE WEHNELT CYLINDER

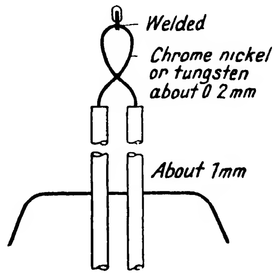
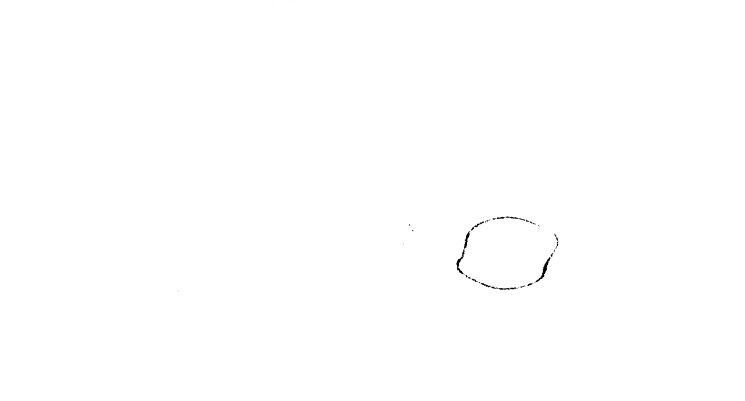


FIG. 110. POINT CATHODE FOR A.C. OR D.C. HEATING

the sharpness of the spot again suffers. These disadvantages are avoided in the more recent type of point cathode shown diagrammatically in Fig. 112. This is a combination of the



(a) (b)

FIG. 111. INFLUENCE OF THE INITIAL FOCUSING ON THE DIAMETER OF THE RAY

(a) Point or modern loop cathode
(b) Old form of loop cathode

loop and hairpin cathode. In this case, the point is the position of maximum temperature.

The point cathode mentioned above represents the first step in the transition to the group of so-called indirectly heated cathodes. In cathodes of this type, as distinct from the directly heated cathode, the emissive point is not right at the surface of the heating wire. The type of indirectly heated cathode, devised by B. Döhring[56] and shown in Fig. 113, shows a certain resemblance to the point cathode of Fig. 110. Inside a nickel cylinder which forms the conductor for the heat developed by the current is the heater spiral, which serves as the second conductor. The oxide mass is on the end of a short wire which is welded on the axis and at the top of the cylinder. A similar construction as an indirectly heated point cathode was used under certain conditions for the older form of gas-filled tube.

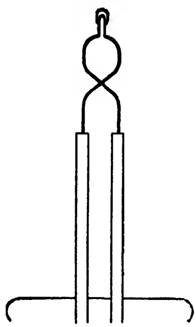


FIG. 112. RECENT FORM OF POINT CATHODE

Quite different suggestions have been made by Chaffee[57] for a type of cathode which was modified later by Schröter[58] and Dobke[59] and known as the "pot" cathode. These cathodes are formed as "black bodies." The oxide material is applied to the walls and bottom of a hollow cylinder, whilst electrons can make their exit through a hole in the top. In this way the opening in the cathode lid, giving release to the internal space charge zone, is used for forming the electron-optical image, and thus the development of an absolutely uniform ray is made possible, so that a circular bright spot is produced on the screen. This cathode is less endangered from ionic bombardment, as the ions which enter the hollow space in the cylinder can only reach the end facing the opening, and the emitting side walls remain undisturbed. One can recognize here the Lilienfeld principle already used by Johnson. The great disadvantage of the pot type of cathode is the very small penetrance of the anode with respect to the cathode.

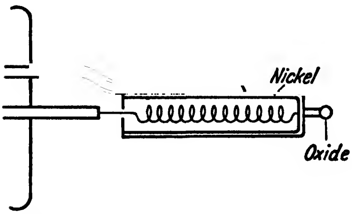


Fig. 113. Indirectly Heated Cathode (*B. Dobking*)

It is therefore necessary to connect an auxiliary electrode of

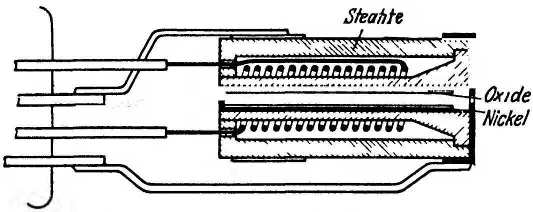


Fig. 114. Indirectly Heated Cathode (*F. Schroter*)

high positive potential immediately in front of the pot cathode. Two types of pot cathodes are shown in Figs. 114 and 115. In Schröter's construction the auxiliary anode is an integral part of the cathode assembly. In this case also the heating coil is insulated from the nickel cylinder used as the oxide carrier, whilst the exterior steatite cylinder serves as a heat insulator and carries the auxiliary anode. In Dobke's arrangement (Fig. 115) the metallic wall of the pot cathode is used

as the return-conductor for the heating current, so that special supports and leads become necessary for the auxiliary anode. In this case, through lack of space, the Wehnelt cylinder can only be accommodated behind the auxiliary anode. In order to prevent complete retardation of the electrons, it is necessary to fit a second anode behind the Wehnelt cathode. The need for the auxiliary anode with hollow cathodes results in the electrons attaining a fairly high velocity before they reach the centre of a brightness control electrode. As the velocity of the individual electrons varies considerably by reason of the irregularity of the accelerating field, a steep brightness control characteristic is scarcely attainable, at any rate with these simple hollow cathodes, so that cathodes of this form could not become of any importance for television tubes. The greatly enlarged photograph, Fig. 116, shows a form of cathode with indirect heating of the oxide carrier, suitable for either

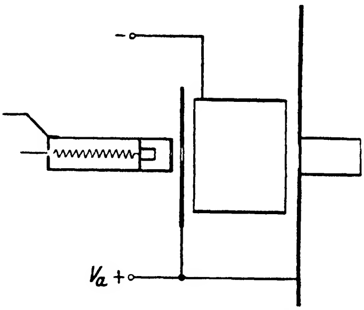


FIG. 115. ELECTRODE ARRANGEMENT AND CIRCUIT OF A.E.G. LOW-VOLTAGE TUBE

FIG. 116. PHOTOGRAPH OF A MODERN INDIRECTLY HEATED CATHODE GREATLY MAGNIFIED FOR HIGH-VACUUM OR GAS-FILLED TUBES

a.c. or d.c. In this case heating is carried out by means of a tungsten spiral arranged inside a small insulating zirconium oxide or quartz tube. The actual oxide carrier shown, which screens the zone of minimum potential in front of the cathode from the stray magnetic field of the heating circuit, and at the same time acts as the return conductor for the heating circuit, is drawn over the small insulating tube. As a rule the pole of the heating circuit connected

to the oxide carrier is indicated at the terminals of the cathode-ray tube, in order to ensure the connexion of the equipotential surface to that pole of the supply mains which is at constant potential. The universal cathode described, which as a rule is designed for a voltage of 3–4 and a current of 0·5 amperes, has a time for heating up which is no longer than that of the cathodes of modern indirectly-heated valves used for broadcasting. In gas-filled tubes having this form of cathode and an accelerating electrode, the oxide is generally fixed in a small boring of 0·2–0·5 mm. diameter, this being in the centre of a plate-shaped end. Special care should be taken to see that no superfluous oxide is left attached to the hole when filling takes place, since otherwise a uniform ray will not be formed, or else disturbances will occur on the screen due to stray electrons.

Extremely stable cathodes which are not easily burned out and which have a short pre-heating time, can be made by simple construction with solid heaters which should be kept as small as possible, or by designing the cathode supports so that the heat conducted away is a minimum.

To obtain a tube with good characteristics, a factor which is equally as important as the type of mounting and forming of the cathode, is that it should be so placed relatively to the system that the field influences the emitting surface to such an extent during operation that the specific load on the oxide is neither too large nor too small. If the accelerating field in front of the cathode is not strong enough, the influence of the space charge gives rise to very small ray currents and characteristics of low slope. In consequence of the small current the amount of metal capable of emission formed subsequently by electrolysis is very small. If the amount formed is smaller than that lost by evaporation, the cathode suffers deformation. On the other hand, the field strength near the cathode must not be too strong, otherwise the supply of oxide available will be consumed too quickly and the life will be perilously short. In designing the first acceleration system, therefore, while considering purely electron-optical factors, the most satisfactory compromise between output and life should be adopted. When designing the field of the first accelerating electrode, a fundamental difference between vacuum and gas-filled tubes must be noted. In the gas-filled tube, where the high space charge which forms in front of the cathode is neutralized by

positive gas ions, a very much smaller potential drop in front of the cathode is sufficient to give rise to the necessary ray current than is required in the high-vacuum tube. The distances between the accelerating electrodes and the cathode, therefore, are much greater for a gas-filled than for a vacuum tube, even when a positive voltage of equal value is applied to the first accelerating electrode. The extent of the potential drop in front of the cathode, and the configuration of the first

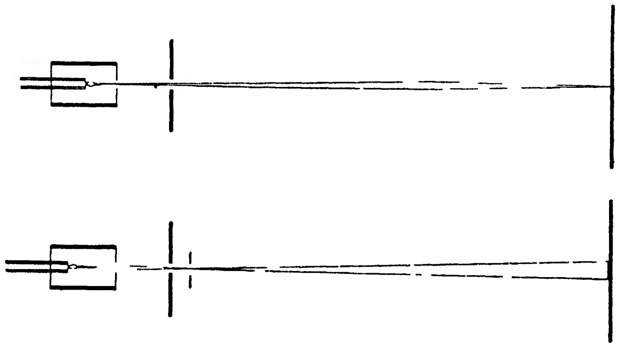


FIG. 117. RAY PATH FOR VARIOUS POSITIONS OF THE CATHODE IN THE WEHNELT CYLINDER

accelerating field, depend largely on the design and bias of the brightness control electrode. The most important points concerning its design for operation in conjunction with the cathode in high-vacuum tubes have been discussed already in earlier chapters. Special points about the arrangement of the Wehnelt cylinder are discussed briefly below. In order to give the most efficient electron-optical focusing, the Wehnelt cylinder must have a definite position which is suitably placed with respect to the cathode, and which is best found by experiment. Fig. 117 illustrates the effect on the path of the ray of various positions of the cathode in the Wehnelt cylinder in an old form of gas-filled tube. If the Wehnelt cylinder is incorrectly placed, a sharp spot on the fluorescent screen cannot be obtained even by increasing the focusing effect, which decreases the life.

With dimensions of component parts and their distances between one another as may occur in practice, e.g. a distance of 10 mm. between the anode and the front edge of the cylinder, the vertical distance *a* between the source of electrons

and front boundary surface of the enclosing cylinder must not exceed half the internal diameter d of the cylinder. This relation $a \leq d/2$, which must be fulfilled in the older gas-filled types, ensures good control and sharpness of the screen spot and has also been recorded by others.[60]

This relation no longer applies to the more recent forms of gas-filled tube with accelerating lens and reduced gas pressure, where the first accelerating field is usually very much weaker and, on account of the surface oxide carrier, the penetrance of the anode is entirely different. Here, the point of emission is generally much nearer the opening of the cylinder.

In mentioning the Wehnelt cylinder in the previous paragraphs, particularly in connexion with systems for gas-filled tubes, it was not intended to refer to the cylindrical electrode type exclusively. In this connexion the cup-shaped electrode of Fig. 102 and the shape of the brightness control electrode in high-vacuum tubes should be borne in mind. In exceptional cases, especially for projecting line-shaped emitting surfaces, focusing electrodes which are not axially symmetrical are also used; for example, electrodes with rectangular cross-section, equipotential plates facing one another, electrode arrangements with elliptical section, strip-shaped apertures, etc., have been used or tried out. In other cases, focusing electrodes similar to parabolic mirrors have been suggested, the filament being placed at the optical focus. These non-axially symmetrical arrangements have one common feature—they are orientated on an axis parallel to the hot cathode. With gas-filled tubes where efficient brightness control by means of a Wehnelt cylinder is required it is advisable to use a jig or optical means of centring to see that the point source of electrons lies exactly at the centre of the Wehnelt cylinder and on the axis of the rest of the system. In high-vacuum tubes, faulty centring, particularly of the brightness control electrode, does not necessarily lead to changes in position of the brightness control, but it does certainly give rise to errors in forming the spot image. On account of the constructional arrangement also, in high-vacuum tubes, care should be taken to see that a symmetrical arrangement is maintained over the whole ray-producing system by using, for example, distance pieces. The parts of the system must be mounted and insulated in such a way that their adjustment is never disturbed, even at a later period when they are heated

(cathode heating, ageing, etc.). Furthermore, it should be ensured that magnetization of points in the system or strong external magnetic fields do not cause a disturbance of the axial symmetry of the system which is the source of the rays.

The most satisfactory dimensions found from the points discussed, with the experimental work of various tube manufacturers as a basis, are obtainable from the various diagrams given in this book, which as far as possible have been kept to scale, and also from the photographs of the electrode arrangements.

(B) ARRANGEMENT OF THE ELECTRODES. There are numerous methods of arranging the electrodes which give rise to the rays, focus and deflect them; and also a wide choice for the selection of the materials used for the electrodes, their construction and the methods of mounting them.

(i) *Materials, Supports and Connexions.* Fundamentally only material which has been vacuum furnaced should be used for all types of electrodes, since this treatment enables the time of heating for the removal of the residual gases to be reduced to a minimum. The materials generally used in their construction are. nickel, chrome-nickel, aluminium, platinum and molybdenum. Nickel is chiefly used as the electrode material (in amplifying valves) since it can be easily welded, is unaffected by high temperature, and resists oxidation.

For high-vacuum tubes it is advisable, in order to avoid the disturbances of centring referred to above, to use chrome-nickel as an electrode material, since it does not possess any residual magnetism. The use of non-magnetic material for construction is advisable in order to avoid distortion of the curve due to the effect of magnetic deflection on the deflecting plates which are not being used. Copper and aluminium, as well as more recent special alloys, are also used as other non-magnetic materials for construction.

Circular or square nickel wires form effective supports for the electrodes. If several electrodes independently supported are to remain insulated from each other, glass or mica is generally used.

Resistance to high temperature necessitates quartz, porcelain or steatite. An important feature of every high-vacuum tube is the current lead through the glass, which must form an air-tight joint. For low currents, platinum or platinum covered wires are used, the support wires being fixed to them on the

vacuum side and on the outside copper braid or tombac* wires. For higher currents of 2 amperes and upwards the conductors and support wires are both attached to a continuous rod of large cross-section, which for use with ordinary glass is of chrome-iron and for special glass of molybdenum, so that the coefficients of expansion of glass and metal are the same. In order that the positions of the components may not alter at high temperatures and to ensure good conductivity of those parts which are electrically connected, the use of the tube must be borne in mind when the method of fixing is decided upon. Electrical spot-welding is the best method for combining extreme rigidity with low contact resistance. Unfortunately, it is not equally suitable for all metals, and those of high conductivity cannot be welded since the heat is rapidly conducted away from the contact. Neither can alloys be welded on account of their low melting point. Further, the welding together of various metals is not in all cases successful. It is often possible, however, in such cases to get over the difficulty by welding a piece of a different metal between the two pieces to be connected together. In most cases, where spot welding is not possible, a firm joint can, in experimental sets, be made by soldering, using hard solder, if mechanical or thermal conditions necessitate it. If soldering is to be done near the lead-in wires, soft solder or even Woods metal must be used. At places where the metal used is unsuitable for soldering, or where even the smallest temperature rise cannot be allowed, the only way is to clip or screw the various component parts together. The method of clipping is not by any means an emergency measure only; it is often an exceedingly useful method of construction in cases where the whole electrode assembly has to be connected to the glass or metal supports.

(ii) *Geometrical Arrangement.* The electrodes which serve as the source of the rays, which focus and deflect them, can in principle be connected together to a single support, the so-called *single base* fitting. A characteristic instance of this type is illustrated in Fig. 118 of the electrode assembly of the Western Electric tube. The great advantage of this arrangement is that the separate parts can be adjusted in position before placing in the bulb, by workers unaccustomed to glass blowing. When the assembly is made, it is only necessary to adjust the whole of it to coincide with the axis of the tube.

* A copper-zinc alloy.

A disadvantage of the construction (Fig. 118) is that if repairs to the cathode are necessary, it is hardly worth while to carry them out, since not only must the foot be disconnected, but practically the whole electrode system must be taken to pieces. In addition, the employment of a single base is limited to use with low frequencies, since the whole assembly has a large capacitance. The connexion of part of the deflecting system to the anode is also a drawback of the single base tube, and is made in order to reduce the number of leading-in wires. The single base fitting is particularly suitable for tubes designed for a special purpose (for television receivers), and in such cases the construction of the tube and the auxiliary equipment can be designed from the start for the particular end in view. The electrode system (of an old tube) shown in Fig. 119, developed and constructed by the author, is somewhat simpler than the Western Electric tube. The chief components are supported by a glass frame similar to that adopted in the older multiple type of tube. This tube can be operated up to 3 000 volts. A special form of pinch and tube base makes it possible to work with such high anode voltages in spite of the single base fitting.

FIG. 118. COMPLETE ELECTRODE SYSTEM MOUNTED ON A GLASS PINCH (OLD WESTERN ELECTRIC TUBE)

In connexion with the electrode system, it should be noted that the glass frame is not let into the end of the glass foot, but at some distance from it. The leading-in wires which are at or near cathode potential are arranged on the inside of the glass frame, and those which are at or near anode potential are fitted outside the glass frame. The increased separation of the electrode assemblies which results enables the tube shown to be operated at several thousand volts.

Fig. 120 illustrates the construction of the system for a

modern high-vacuum tube developed with a single base fitting. The arrangement is produced in tubes for television as well as for measuring purposes, with two and four deflection plates. The deflecting plates are led out separately through the base

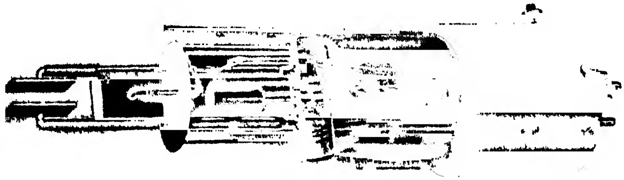


FIG. 119 ELECTRODE MOUNTING OF AN OLD TYPE GAS-FILLED TUBE USING A GLASS FRAME

so that a symmetrical deflecting voltage may be applied. Here, also, the various electrodes are supported by a glass frame. By suitable grouping of the leading wires in the pinch, it has been possible to increase the distances between the leads so that the tube can be operated safely at anode voltage of 4 000–5 000 in spite of the single base fitting. The capping is arranged

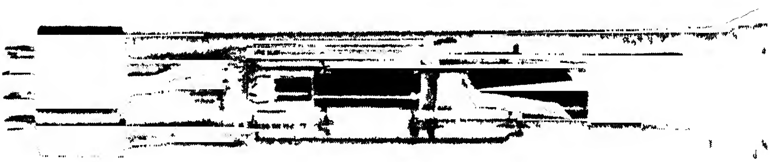


FIG. 120 CONSTRUCTIONAL ARRANGEMENT OF A HIGH VACUUM TELEVISION TUBE WITH FOUR PLATES LED OUT SEPARATELY TO THE BASE
(Single base mounting type AE 225)

as shown in Fig. 121, so that the pins at or near cathode potential and those at or near anode potential are well separated

The single base construction makes the problem of constructing larger sizes much easier. It enables greater precision of working to be carried out by the assistance of tools, jigs, and moulds.

The main disadvantage of the single base construction,

compared with tubes having the deflecting plates brought out at the side, even when well designed, is the greater capacitance between the sets of deflecting plates, which may amount to 5 $\mu\mu F$. The coupling of the two pairs of plates at a given deflection frequently produces disturbances when sources of high internal resistance are applied simultaneously to the ordinate and abscissa plates. Consequently, the single base fitting is used primarily in tubes designed for television and constructed specially for low-frequency measurement. The construction of the electrode assembly will become clearer when

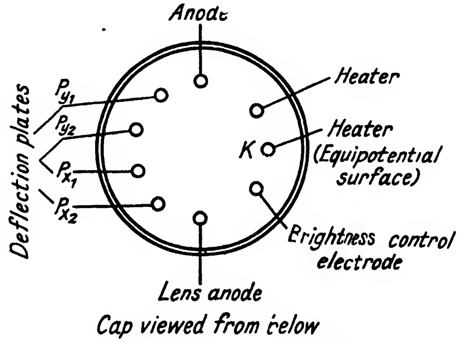


FIG. 121. THE VARIOUS CONNEXIONS OF A MODERN ELECTRON-RAY TUBE AND AN EXAMPLE OF THE CAPPING

the electrode system producing the deflection is separated from the system where the rays originate. In the low-voltage tube, Fig. 122, manufactured by the A.E.G., the deflecting system and origin of the rays are separated both electrically and spatially, although the former is still connected by a glass ring.

Although the deflecting system forms a single unit, each plate is led out separately to avoid capacitance effects. For anode voltages over 5 000 it is necessary to take the anode lead-in wire and the leads to the deflection plates out of the base, and fix the anode and plates to special supports which at the same time serve as leading-in wires. This form of electrode arrangement is used in the larger sizes of tubes, for very high tracing speeds. The leading out of the electrodes at the side, as distinct from the single base type, necessitates the employment of skilled glass blowers.

Fig. 123 shows an electrode arrangement which has no plate

deflecting system and is therefore suitable for magnetic deflection. A peculiarity of this model, which was early developed by Zworykin as a high-vacuum system for television, is the method

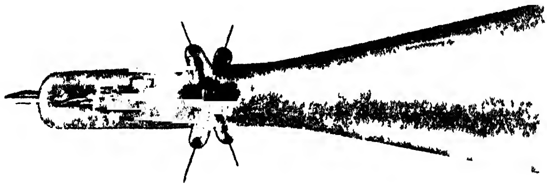


FIG. 122. CONSTRUCTION OF THE A.E.G. TUBE

of supporting part of the electrode system by the small bell-shaped attachment round the glass neck, and further the metallic covering on the inner wall of the bulb which can be formed by silvering or by using a mesh arrangement for delayed acceleration. A discussion on the dimensions of the deflecting plates can be found in the section dealing with electrostatic control. The constructional limits to the length of the deflecting

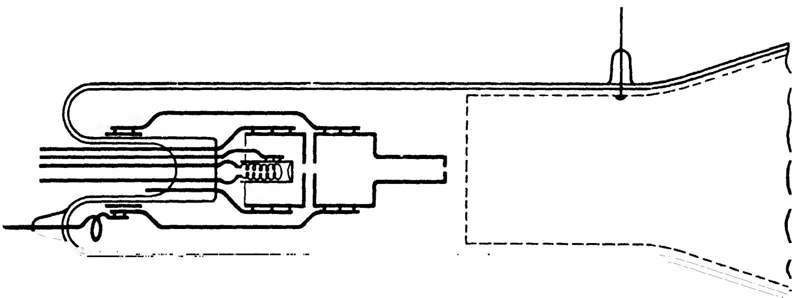


FIG. 123. ELECTRODE CONSTRUCTION OF AN OLD TYPE OF HIGH-VACUUM TUBE (*Zworykin*)

plates have been discussed in this section, and in the one relating to the time of passage of the electrons, when working with very high frequencies. The distance between the deflecting plates which should be kept small to ensure greater sensitivity, cannot be reduced to any limit desired partly for electrical and partly for mechanical reasons. Finally, however, a large divergence of the ray causes it to come in contact with the plate at the

end nearest the screen. In order to restrict this effect, slanting plates have been used for tubes with large screens.[61]

(c) Gas Pressure and Gas Filling. In high-vacuum tubes, brightness and contrast of the image or oscillogram figures depend on the extent it is possible to maintain a low pressure of 10^{-6} to 10^{-7} mm. Hg for long periods of operation. In general, the principles which are generally used for the construction of high-vacuum amplifying valves should be followed here. Different conditions exist only in respect of the appearance of residual gas, due partly to the high accelerating voltages which attack the cathode very much more strongly. The high-vacuum technique of modern cathode-ray tubes is, therefore, not unlike that for the production of transmitting valves. The prevention of gas appearing in the manufacture of gas-filled tubes, and especially of the later types with reduced gas pressure, is just as important for the life and stabilization of the properties of the tube as for high-vacuum tubes, for uniform pressure and unaltered composition of the filling gas are conditions for stability of the characteristics of gas-filled electron tubes.

The de-gassing process for a modern gas-filled tube is therefore not greatly different from that of a high-vacuum tube. In spite of the prominent position occupied by the high-vacuum tube to-day, the gas-filled type is of importance for measurements in the low-frequency range where one is compelled—in view of the available current sources, or high deflection sensitivities to be obtained—to work with low anode voltages; for at low accelerating voltages the unavoidable disturbances (e.g. velocity distribution due to temperature change) have a critical influence on the quality of the image. For modern tubes, therefore, gas-fillings which give good focusing and low electron diffusion at low anode voltages are to be preferred. Argon and sometimes helium is used for ordinary cathode-ray tubes.

Helium and to a greater extent hydrogen exhibit very great losses by electron diffusion. They are to be recommended only for special problems where gas-focusing at anode voltages up to 6 000 is required.

For very low anode voltages, the heavy rare gases are used (krypton and xenon), since they reduce greatly the electron loss by diffusion.

At the same time it becomes evident that with these two

gases, the secondary illumination depicted in Figs. 27 and 29 is reduced. With these heavy rare gases, however, the focusing anomaly already discussed above appears between the limits of high- and low-frequency.

Simple experimental tubes are also often filled with mercury vapour, which has good focusing properties. Unfortunately, it is greatly affected by temperature and the point of lowest temperature in the tube determines the pressure. In order to maintain a certain pressure in the tube for operation it must be thermally insulated where necessary.

If fillings with other gases besides those mentioned are to be considered, the essential requirement is that the gas must be chemically inactive with respect to the hot cathode. The adjustment of the maximum gas pressure in the tube is equally as important as the choice of gas. With the lighter gas-fillings (e.g. hydrogen or helium) the optimum pressure is of the order of ten times that required for the gases of high atomic weight. The optimum pressure of a tube operating with gas-focusing is to be understood as the lowest pressure at which, with normal cathode heating and anode voltage, there is a considerable excess of ions formed by the ray. The excess must be great enough for the gas-focusing effect to be maintained even if the emissivity of the cathode falls, in the course of operation and dark control is exercised on 15–20 per cent of the normal ray stream. Whereas the optimum pressure for argon and the old electrode system with Wehnelt cylinder and one anode is about 5×10^{-3} mm. Hg, that for argon in more modern systems with accelerating lenses is nearly one-tenth of this value. It might be assumed that the system for producing rays giving small spots in high vacuum would operate with some gas, since the focusing effect occurs at very low pressures. This assumption is not correct. In fact, such electron-optical systems operate satisfactorily with very low gas pressure when no large section of rays exist anywhere between cathode and screen in the high vacuum. This is the reason why the simple system with one accelerating lens discussed above gives particularly good results. Improvement of the ray-producing system, enabling the pressure to be reduced, results not only in an increase of life and stability, but a reduction in deflectional errors and an improvement in the sharpness of the spot; it produces also an increase in the brightness of the spot by reducing

electron diffusion in the gas section and a reduction of diffused light on the screen.

The measurements in Fig. 124 provide a survey of the magnitude of the losses by electron diffusion in the gas with the older simple system. The measurements prove that the value of the effective ray current in these older gas-filled tubes was not much greater than the corresponding value in modern high-vacuum tubes.

(D) THE FLUORESCENT SCREEN. Whereas all the components of the tube hitherto described—cathode, focusing system

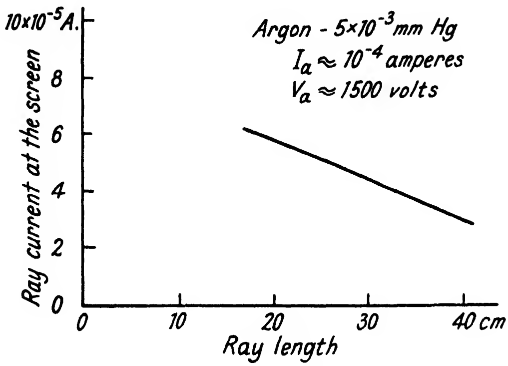


FIG. 124. RAY CURRENT AT THE SCREEN IN RELATION TO THE LENGTH OF THE RAY FOR A GAS PRESSURE APPROPRIATE TO OLD GAS-FILLED TUBES

and deflecting electrodes—serve to produce the means of tracing an oscillation, the actual tracing occurs on the screen. The performance of an oscillograph depends, therefore, on the screen, as well as on the components producing and controlling the rays. The function of the screen is to convert the kinetic energy of the mobile electrons into the greatest amount of luminous energy at all points of its surface on which the cathode rays fall. The physical properties of a fluorescent screen must be completely known before any idea of its suitability can be given.

(i) *Requirements of a Screen.* The requirements of an efficient oscillograph screen are: the greatest possible luminous efficiency at that part of the spectrum which coincides with the peak sensitivity of the photographic film or plate; and, if possible, a gradation curve, the range of which is such that the screen is not excited by stray electrons of low velocity.

Further, absence of luminous halos is desirable, and many purposes require as little after-glow as possible. A fluorescent screen which meets the optical requirements specified does not necessarily fulfil the conditions required for operating a sealed-off cathode-ray tube. In fact the screen must be stable during the life of the tube, and there must be no appearance of breakdown or burning with ray energies which may be used. Particularly when high tracing speeds are employed the best-known screen materials show signs of breaking down and burning, especially when the ray is not deflected and its whole energy is concentrated on to one small spot on the screen. The type of screen needed for high tracing speeds should also possess the characteristic of recovery after fatigue. Certain types of tubes require adequate electrical conductivity. All these requirements can be satisfied by using suitable manufacturing processes and materials for the screen.

(ii) *Screen Materials*. The intensity H at which the screen material becomes luminous when bombarded by electrons is calculated from the Lenard law

$$H = \eta \cdot n(V - V_0) \qquad (41)$$

where η is a constant* of the material, n the number of particles per sec. on 1 cm.^{2} of surface, V the applied anode voltage, and V_0 the minimum exciting voltage of the fluorescent material.

In view of the limited number of excitable centres of the material, this equation does not hold good for values above a certain brightness. Even at very low brightness values, the equation is only approximately true. The beam voltage V_0 expresses the fact that most phosphorescent substances are not excited by electrons moving with less than a minimum velocity V_0. V_0 does not depend only on the material since it can be increased by altering the nature of the embedding of each particle of the phosphorescent material in the binding substance which is necessary for the manufacture of the screen. This is shown clearly by the gradation curves reproduced in this chapter of fluorescent screens with and without binders. The beam velocity with some phosphors corresponds to very low voltages, less than 50 volts. These phosphors are particularly suitable for use in low-voltage tubes, but less so in tubes where anode voltages of several thousand are used, and

* How far this term can be considered constant is discussed more fully later on (Chapter IV).

where stray electrons have mean velocities higher than that corresponding to the minimum exciting threshold.

In view of the dependence of practical recording instruments on spectral distribution—whether it be the human eye or one or other of the photographic emulsions—the selection of materials must always be confined to those substances whose fluorescent light is a maximum in the range of the registering instrument. A large collection of details concerning fluorescence material for cathode-ray tubes has already been published.(62)

The author will confine his attention in this section to giving quantitative data of the peculiarities of the most important screen substances.(63). In particular, measurements of efficiency of illumination and distribution of spectral intensity will be given. The luminous efficiencies determined by a Pulfrich photometer are tabulated in Table I. The best result at relatively high basic screen loading is given by material No. 15,

TABLE I

Material No.	Description	Efficiency Hefner Candles per Watt
1	Old television screen, sepia, with after glow	1·06
2	Leybold-Standard measuring screen, green-yellow (530 mμ), non-after-glowing	3·50
3	Zinc cadmium sulphide, yellow	1·6
4	Coss. V.S. 34, matt-green	0·86
5	Zinc silicate (S. 101) green	0·86
6	Zinc silicate Cu, green	0·48
7	Manganese silicate red, very pronounced after-glow (sensitive to burning)	0·15
8	A. No. 32, zinc silicate, yellow	0·53
9	A. No. 36, zinc silicate, yellow	0·28
10	Zinc sulphide, yellow	1·54
11	A. Ch. 40 H, zinc sulphide, green-yellow	3·30
12	Calcium tungstate, blue	0·23
13	Cadmium tungstate, yellow-blue	0·70
14	Zinc sulphide, blue-green, with after-glow	1·75
15	Leybold measuring screen, yellow-green (550 mμ), no after-glow, sensitive to burns	4·5
16	Zinc sulphide yellow, pronounced after-glow	2·15
17	Lorenz-Leybold-Standard television screen, white, slight after-glow	3·5

Efficiency factors measured from transparent screens (V_a = 4 000 volts measured at 0·05 watts/cm.^{2}).

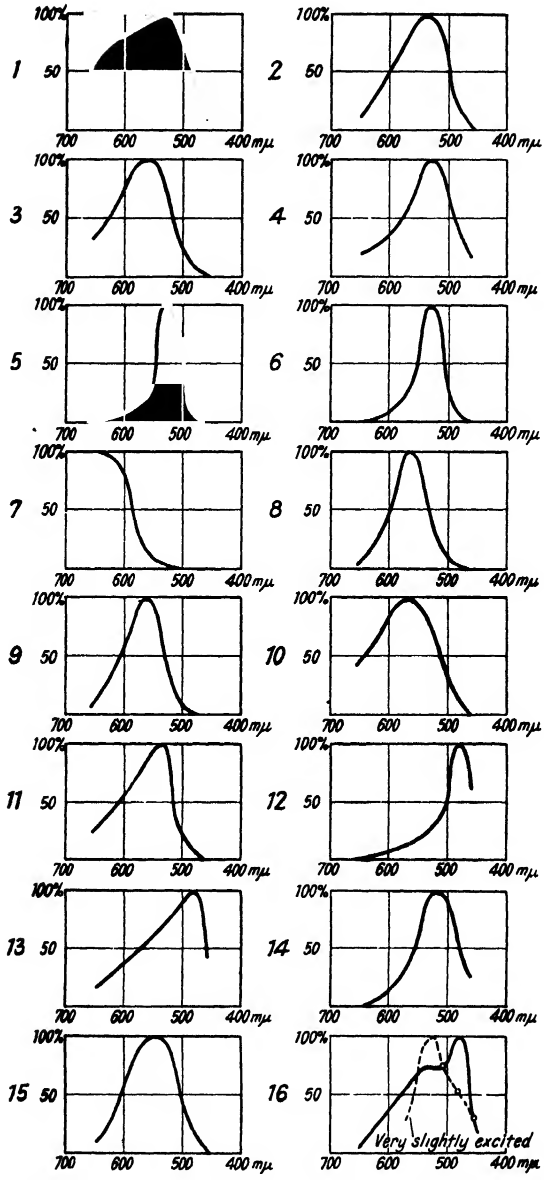


FIG. 125. SPECTRAL INTENSITY DISTRIBUTION OF A NUMBER OF FLUORESCENT MATERIALS

which, however, is not suitable for all measuring purposes on account of its tendency to burn, and is in addition useless for television purposes on account of its spectral distribution curve which is unpleasant to the eye. The extremely instructive curves of spectral distribution obtained from the screens investigated for their efficiency in producing visual impressions are given in relative values in Fig. 125. The distribution curve of material No. 17 is shown separately in Fig. 126 for various degrees of screen loading. The outline recorded for materials 1, 16, and 17 is extremely interesting. These substances have two spectral bands which are excited to a different degree according to the varying intensity of the ray current. Measurements made on material 16 show that at a higher specific loading the peak is at about 480 mμ, whilst for less intense loading the second band predominates, and the peak appears at about 540 mμ.

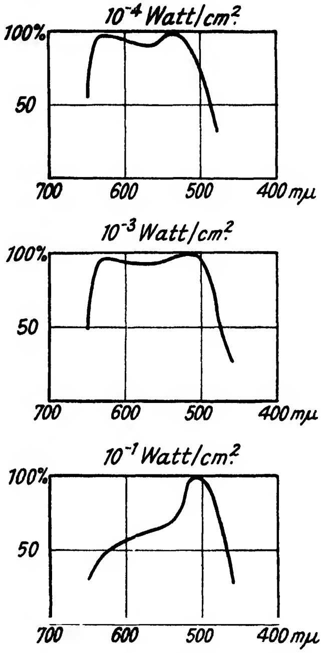


FIG. 126. SPECTRAL INTENSITY DISTRIBUTION FOR VARIOUS SPECIFIC LOADS WITH A WHITISH TELEVISION SCREEN

(Material No. 17, V_a 4 000 volts)

Televised pictures on this fluorescent material have the peculiarity that the dark sections are tinted brown and the light sections of a whiter tint. The explanation of this behaviour is given by the measurements shown in Fig. 127. The longer wave band is due to phosphorescence and the shorter band to fluorescence. As the phosphorescence, as distinct from the fluorescence, exhibits definite saturation, the amplitude ratio of both bands, i.e. of the colour as well as the intensity, must change with the specific loading of the screen. In television reception, the specific loading is of the order of 10^{-3} to 10^{-4} watts/cm.^{2} The behaviour of the screen under conditions of very feeble excitation is therefore the only one of any consequence. Here the luminous efficiency is much more favourable, as shown by the measurements in Fig. 127, than in

the table given above which was compiled from measurements made under conditions of higher specific loading. The highest efficiency consistent with the most favourable spectral intensity distribution at loads of 10^{-3} watts/cm.^{2} was found to be given by material 17 of the table which, from 630–500 mμ, supplies more than 90 per cent of the maximum intensity of radiation and appears pure white to the eye. The results of measurement given above show extraordinary differences in the spectral intensity distribution of various materials. Whereas the highest possible photographic efficiency is required when used as an

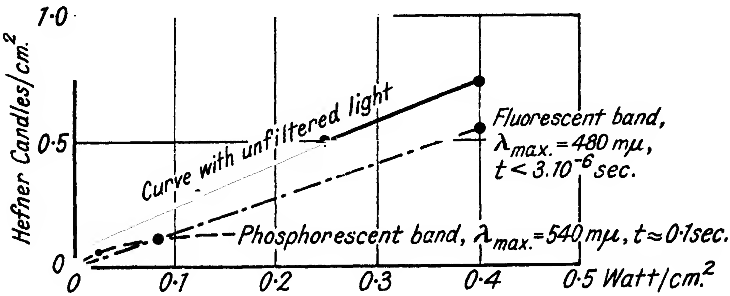


FIG. 127. MEASUREMENTS TO EXPLAIN THE RELATION OF THE COLOUR AND THE EFFICIENCY OF THE SCREEN ON THE SPECIFIC LOAD WITH THE FLUORESCENT MATERIALS OF TYPE NOS. 1, 16, 17

oscillograph, there is the additional condition that the colour shall be pleasant to the eye when the cathode-ray tube is used in a television receiver. Fundamentally, it would appear that those materials which have high luminous efficiency only in narrow spectral bands (see curves 5, 6, and 12; Fig. 125) are of no value for television. Calcium tungstate, in spite of its low visual efficiency, is still of value nowadays for photographic recording. Material No. 2 for most emulsions (e.g. Agfa-Isochrom plates) is about the same as calcium tungstate for photographic purposes, but is more suitable for general purposes on account of its high visual efficiency and short after-glow.

The after-glow of the fluorescent screen is an extremely important factor, since it limits a number of possibilities of the cathode-ray tube such as its use in television transmitters, as a source of light whose intensity is controlled at high frequency, and the resolution of the oscillogram with mechanical time deflection. The way in which the screen is affected by

frequency, which is determined by the after-glow, can be found with the assistance of calibrated high-vacuum photo-electric cells and special valve measuring equipment, the intensity of the ray being modulated 100 per cent at various frequencies.

Measurement of the resulting light fluctuation which is synchronous with the modulation frequency, reveals a peculiar performance which is common to most luminous materials. Fig. 128 shows the results of measurements made on several

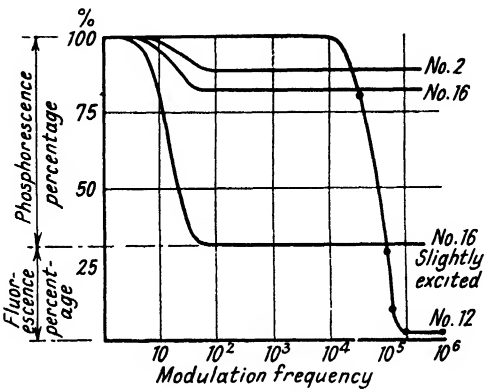


FIG. 128. DEGREE OF MODULATION OF THE SCREEN ILLUMINATION FOR VARIOUS MATERIALS WITH 100 PER CENT MODULATION OF THE RAY ENERGY AS A FUNCTION OF THE FREQUENCY

luminous materials which are either important in practice or are of special interest. For calcium tungstate (No. 12) the percentage fluctuation remains constant in the range of medium frequencies, and then decreases very rapidly as soon as the periodicity of the modulation approximates to the time of after-glow.

Strange as it may seem, the degree of modulation does not approximate to zero, but to a constant value of the order of 1·5 per cent. Even with frequencies of 10^6 cyc. this degree of modulation is maintained in spite of the fact that the after-glow is about 10^{-5} sec. The result of this observation forces us to the conclusion that the so-called *fluorescent light* of the calcium tungstate is composed of two components. The first component is a highly efficient illumination with an after-glow of about 10^{-5} sec., which has been described hitherto as fluorescence, but which ought to have been termed phosphorescence. The

second component is indicated by the actual fluorescence which has a small after-glow—too small to measure, possibly 10^{-8} sec.—and is analogous to optical fluorescence and is about 100 times less effective over the spectral range. This great difference in efficiency of the materials in common use results in the phosphorescence completely overpowering the non-persistent fluorescent light and the distinction between the two would need special apparatus for segregation and separate measurement.

Measurement of the other substances shows that the after-glow of the phosphorescent components is very much greater than in the case of calcium tungstate. The phosphorescence of material No. 2 in particular is, however, shown to be only slightly greater than 10 per cent of the total, so that compared with non-persistent fluorescence which occurs in practice it can almost always be ignored. This substance, therefore, opens up interesting possibilities for the use of the cathode-ray tube as a h.f. light source in cathode-ray scanning transmitters, and for other purposes where extremely low screen after-glow is required.

(iii) *Process of Manufacture.* The properties of the materials of the various fluorescent substances enumerated in the foregoing section can be affected most by the method of production. treatment, and the mode of applying to the actual screen carrier. As far as the substance is concerned, its crystalline form and the particle size contribute enormously to the final efficiency of the screen. The crystalline form is affected by the method of chemical formation, the grain size and the degree of mechanical pulverization. Fineness of grain must not be secured merely by grinding in a mortar in the usual way, since the sensitivity of the mass of the material may suffer severely from such treatment. Rather is it expedient to take such care as to ensure that the desired grain size is not exceeded during the process of crystallization. If a fluorescent substance of the required quality is available it can be applied to the screen carrier in various ways, with or without a binding substance. The best-known binders are sodium and potassium silicate, and the simplest silicate process consists in mixing the fluorescent material and binder together and applying them to the screen carrier with a small brush. Screen surfaces constructed in this way are, however, very uneven. In addition, the enclosure of the crystal results as a rule in a considerable

reduction in luminosity (at 4 000 volts it may amount to 25 per cent). Much higher sensitivity and greater uniformity is obtained by covering the screen carrier with very thin layers of silicate, and dusting the fluorescent substance on to it by means of a fine gauze sieve or similar contrivance. Screens with silica binders show slight burns, brown discoloration and fatigue at high specific loads (down to 10 ^{2} watt/cm.^{2}). Sodium salts are the cause of the colouring since the action of the cathode ray causes reduction of the salt with separation of sodium to take place. Potassium silicate is the most satisfactory. For television work, screens made with silicate are eminently suitable on account of the fact that their tendency to show halo effects is small.

An intermediate form of screen between that with and without binder consists of one to which the fluorescent mass is applied in alcoholic suspension. This is prepared so that the suspension corresponds to the required thickness of the layer and is poured into the bulb, so that the luminous particles can sink to the bottom of the mass by their own weight. The alcohol is then removed by suction or evaporation and a screen practically free from binder and of great evenness remains. These screens are, however, extremely susceptible to damage from mechanical vibration, and large portions of the fluorescent mass may become detached from the screen carrier when it is subjected to violent shock during transport. A process of screen manufacture which has attained importance in practice and facilitated the manufacture of thin even screens capable of resisting heat and mechanical shocks, consists of impregnating the glass and is carried out in the following way.[64] The area of the bowl of the bulb to which the fluorescent substance is to be applied is first moistened evenly with distilled water, then an even film of the fluorescence material is dusted on by means of a sieve.

The bulb is next heated slowly until the glass softens at about 500° C. A certain proportion of the particles of the substance sinks into the surface of the glass. After cooling, those particles of the fluorescent substance which have not impregnated the glass are removed with a small brush. By this process, a screen resembling opal glass is obtained, the fluorescent light from which appears equally bright when viewed from either side. Embedding the particles of the materials in the glass results in better heat conduction, so that

the screen stands up to heat better than those produced by the methods previously described. This method of manufacture can be carried even further by mixing powdered glass of low melting point with the fluorescent material to be embedded and so still further strengthen the fixation of the material. The sintering process is, however, limited to a few substances which can stand heating in air until the glass softens, e.g. calcium or cadmium tungstate.

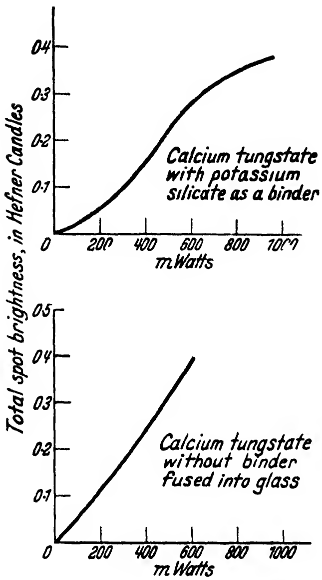


Fig. 129. Gradation Curves of Fluorescent Screens With and Without Binders

The ordinary impregnated screens have very low minimum exciting voltages, and particularly high efficiency even at high electron velocities due to the absence of a binder. This is shown by the gradation curves of Fig. 129. The upper curve is that of a calcium tungstate screen in a thick layer of potassium silicate as a binder; the lower one represents an impregnated screen. The increased efficiency is brought about by raising the anode voltage and by the aid of optimum focusing. Equality in the energies of the rays was secured by having both screens in one bulb. The measurements were made independent of saturation by spreading the energy of the rays over a large surface (deflection in both co-ordinates).

Permanent damage to the screen can occur with rays of high energy even with screens manufactured without a binder. Heating the screen over a flame often brings about a certain amount of recovery, but such heating must be done gradually (in an incandescent flame) to prevent sudden expansion of the glass.

When very slow cathode rays impinge on the fluorescent material even if their velocity is greater than the minimum exciting velocity of the material, the screen may show no illumination. Such a case in which the screen does not provide sufficient secondary emission is illustrated in Fig. 130. In this instance the ray is retarded directly in front of the screen owing

to the considerable charge on the screen. If the screen were connected to the anode, other conditions being the same, this phenomenon would not occur. Careful observation shows that complete darkness exists even in the vicinity of the point of impact on the screen. Even the feeble secondary light which results from stray electrons and which is to be observed in other

FIG. 130. SLOW SPEED RAY (100 V.) BROUGHT TO FOCUS ON THE FLUORESCENT SCREEN

parts of the screen cannot be seen. Charging of the screen is noticeable even with higher anode voltages, although it does not actually produce retardation of the rays. It reduces the electron velocity, which is not the same for all zones of the screen, and it may give rise to a small side deflection of the position of the spot when great differences in the conductivity of the screen exist. In order to increase the screen conductivity with a view to avoiding retardation of the slow-moving electrons, it is possible in principle to attach the screen in thin layers on metal plates or metallized glass surfaces(52). The screen can, however, only then be viewed from the inside of the tube. A polished metal backing has the advantage that it reflects the light rays falling on the metal to the internal side of the screen, and so increases the lighting effect of the surface. If

transparency is essential, the layers must be extremely thin so that the gain in conductivity would only be small. Semi-conducting glass does not appear to produce any improvement.

Dusting the metal film on the front of the screen also leads to considerable losses at the relatively low electron velocities of the low voltage tube, since a large proportion of the electrons are absorbed even by very thin metallic layers. The improvement of the tube due to screen conductivity is usually very small, and is more than counterbalanced by the disadvantages mentioned and manufacturing difficulties. Consequently, gas-filled tubes with transparent conducting fluorescent screens have not so far found much favour in practice.

(iv) *Geometrical Arrangement.* The fluorescent screen of the first types of tube was generally fitted to a special mica or metal plate which was fixed to the interior of the bulb. This method of construction enables the preparation of the screen to be done quite easily outside the bulb, but it has this disadvantage that the insertion of the screen into the bulb is troublesome, and further, it cannot be fixed without glass supports or metal leads fused into the glass. The reason for inserting even surfaced screens into the bulb is not the ease of manufacture only, but partly also for optical reasons (elimination of halos). Furthermore the distortions, though generally small enough to ignore, which are usually associated with screens applied to the surface of the bulb which is curved for constructional reasons, do not occur.

By far the most usual type of fluorescent screen to-day for television as well as measurement is that in which the substance is applied directly to the rounded glass bulb. As the entire surface right up to the edge of the screen is not used, the distortions referred to in more detail later on, in the section dealing with "Precision of Measurement with Cathode-ray Tubes," can be kept reasonably small. Distortions caused by striations of the glass are not present when the screens are viewed from behind. These screens are particularly suitable for a number of purposes where it is necessary to work extremely close to the screen as in contact photography. As observation of screens fitted directly to the bottom of the bulb is carried out usually from behind, care must be taken that the fluorescent material is applied in a perfectly definite thickness, the optimum thickness being obtained when the luminosity at the front is only slightly greater than from behind. Thin

fluorescent screens with almost equal luminosity on either side give less illumination than thicker screens which are, where possible, placed on a reflecting plate and are only suitable for frontal observation. There has not been any dearth of ideas for constructing fluorescent screens with luminosity on one side only. In the first Braun tubes, suggestions were made that the fluorescent screen should be arranged at an angle of 45° to the axis of the tube. The distortion caused by inclining the screen can be avoided in visual observation by viewing it in

FIG 131. A FLAT SCREEN BULB

such a direction that the angle of incidence of the line of sight is approximately the same as the angle of incidence of the stationary ray on the screen Distortion caused by striations in the glass are much more apparent to visual observation than by optical means with large aperture lenses. In order to facilitate photography of the screen patterns with high-power lenses when the screen is inclined, the shape of the tube must be such that the axis of the lens system is perpendicular to the surface of the screen. Distortion in the tracing due to the inclination of the screen can be avoided in gas-filled tubes by suitable correction devices in the deflecting system.

The method of correcting distortion which results in the production of very irregular deflecting fields is not possible in high-vacuum tubes in view of the large ray section. Inclination of the screen is not usually of much use in high vacuum

tubes because the sharpness of the image suffers.* In this connexion it may be mentioned that the lack of sharpness due to inclination in high-vacuum tubes can be corrected by superimposing on the lens voltage the deflection voltage which exists in the corresponding co-ordinate direction (in correct phase and amplitude). In this way the control of slot width of the main electron condenser is secured, and this enables a uniformly sharp image to be obtained even with inclined screens. In order to compensate the deflection distortion in high-vacuum tubes mentioned above, it is necessary to have some control on the amplitude of the deflection voltages. A method of doing this, showing the necessary circuit connexions, is given in a recent paper.† The processes indicated necessitate such expensive equipment that they are usually not worth while unless there are special reasons, as for instance in the case of the iconoscope or similar devices. The recent increase in efficiency of the high-vacuum type of tube makes the possibility of projecting oscillograms and television pictures of considerable importance. With anode voltages of 4 000–5 000 and new screens of high efficiency, projections can be made on to a surface of 0·25 to 1·0 sq. metre or more with sufficient illumination. The large sizes of picture possible with this combination are particularly advantageous for demonstrations to a large audience, especially for showing curves at lectures. Projection on to screens at the front side has the disadvantage that the condenser cannot be brought sufficiently close to the screen surface. One is therefore forced to use long focus systems, and consequently, in view of expense, condensers which are optically less powerful. The advantage of greater brightness is lost again as a result of the optical arrangement. The optical conditions are more favourable with transparent screens where the latter are brought close up to the ray-producing and deflecting system, and the optical projection system can be brought close up to the surface of the screen. A limit to the minimum size of the image on the screen is set by the grain size of the screen surface, the changes in colour, and saturation and fatigue of the material of which the screen is composed.

* M. von Ardenne described this in a lecture entitled "Uber einige Themen aus dem Fernsehgebiet" at the Television Congress, Berlin, 12th June, 1933.

† R. D. Kell, A. V. Bedford, and M. A. Trainer: "An Experimental Television System," *Proc. I.R.E.*, Vol. 22, No. 11, November, 1934.

Fig. 132 shows an interesting type of fluorescent screen for projection purposes. The bottom of the tube is made concave inwards to enable projection to be made with an optical system uncorrected for spherical aberration, and to obtain on the screen a picture which is sharp up to the edges. The type of screen which is affixed to a flat glass plate constituting the bottom of the bulb, an arrangement which has been suggested many times, has never been adopted in practice. The difficulty of securing a constant vacuum by cementing the plane glass plate to the bulb so that it will safely withstand heat without separating, is so great that it becomes prohibitive in cost.

Recently, however, the form of screen shown in Fig. 131 has come into use particularly for projection television tubes as well as for measuring tubes. A bulb having very strong glass

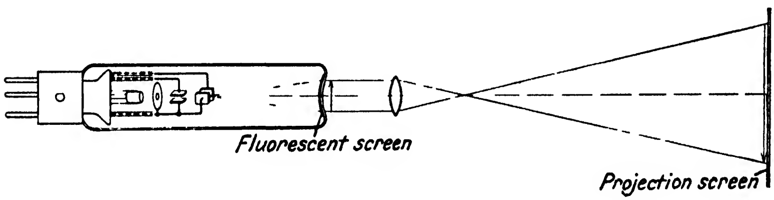


FIG. 132. AN OLD ARRANGEMENT FOR PROJECTING THE SCREEN IMAGE

walls is employed and the bottom is shaped as a flat plane by a special process during manufacture. Later the flat plane is ground and polished on the outside. With a screen diameter of 12 cm. the plane section has a glass thickness of 5 to 6 mm. This construction secures practically all the optical advantages of tubes with cemented planes without the disadvantages associated with their production, already mentioned.

(v) *Significance and Elimination of Halos and Disturbances on the Screen due to them.* With normal screens a phenomenon occurs which brings about a more or less intense secondary illumination in some parts of the screen which are not directly touched by the cathode ray, and which should therefore be absolutely dark. Two photographs of the light distribution around the spot are shown in Figs. 133 (*a*) and (*b*). The disturbance which appears as a halo round the fluorescent spot is due to total reflection at the outer surface of the glass. Its origin is chiefly an optical one.[65]

The mode of formation of the halo is shown diagrammatically in Fig. 134. The cathode rays produce the luminous spot L on the fluorescent screen S. Rays of light emanate uniformly in all directions from this spot. The only portion of the light which can be considered useful for external observation is that which passes through the glass G embraced by a hemisphere facing outwards. But of this portion only the light rays included within a solid angle of 90° can be observed. This solid angle is determined by the critical angle β at which total

(*a*) (*b*)

FIG. 133. FLUORESCENT SPOTS WITH HALOS

reflection takes place, and which is slightly less than 45° for the surface of separation of glass and air. All light reaching the surface of separation at an angle greater than the critical angle suffers total reflection, and leads to the formation of a halo, since the screen has the optical properties of a matt surface (Fig. 134). The useful portion which goes into the outer hemisphere is therefore only about 30 per cent of the whole, assuming that radiation from the spot is equal in all directions. The remaining 70 per cent is totally reflected and results in the formation of a halo. But as, on the one hand, the radiation from the light spot is weaker in the direction of the fluorescent screen, and on the other hand the screen reflects part of the light outwards, the portion wasted does not amount to 70 per cent, but only to about 30–50 per cent in practice. This means that a television picture, for instance, with the screen on the bottom of the bulb, can, in so far as the method of uniting the crystals results in a good optical contact with the glass walls, for optical reasons alone only have a contrast ratio of 1 : 2 to 1 : 3.

This contrast ratio is not by any means sufficient as experiments have shown. The elimination of the halo is one of the chief problems associated with television, and is also of great importance where the tubes are used as measuring apparatus, since its elimination results in increased definition and brilliancy of the figures. There are various possible ways of getting rid of the halo. Two consist of arranging the optical conditions so that the radius of the halo is greater than the effective diameter of the screen or of the diagonal of the picture, or else making it the same size as the fluorescent spot itself. The construction of cathode-ray tubes is entirely concerned with a surface of separation involving glass and air. As the critical angle for total reflection approximates to 45°, the geometrical requirements are that the radius of the halo shall be twice the thickness of the wall of the bulb. For instance, with a glass wall 1 mm. in thickness the diameter of the halo is 4 mm. In order, therefore, that the radius of the halo should be equal to the effective diameter of the fluorescent screen the glass walls would have to be about 4 cm. thick with tubes of the dimensions at present in use. Glass of such thickness is obviously impossible for technical reasons alone. The second method mentioned above—making the halo very small—is not possible if the fluorescent screen is impregnated deeply into the bowl of the bulb, or is applied with one of the usual binders. The diameter of the fluorescent spot in modern tubes is about $\frac{1}{2}$–1 mm. Therefore, according to the relation given above, the wall of the glass should be $\frac{1}{10}$ mm. thick. This thickness would be insufficient to withstand atmospheric pressure. The difficulty can be overcome by arranging the fluorescent screen on a thin-walled transparent support—separated from the bowl of the bulb. Fluorescent screens of this nature, for instance on a metal plate, were discussed in the last section. Freedom from light halos, as well as small optical distortions caused by striations in the glass bowl,

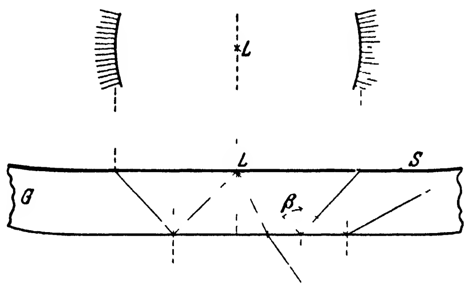


FIG. 134. FORMATION OF HALO THROUGH TOTAL REFLECTION AT THE OUTSIDE SURFACE OF THE GLASS

is secured since the space between the bulb and carrier can be made very small with thin screens (e.g. mica plates; see Fig. 135). This space need only be sufficiently great to prevent actual contact between the bowl and the screen carrier over any portion of the effective surface. Total reflection cannot occur at the surface of separation of the bowl and the air as

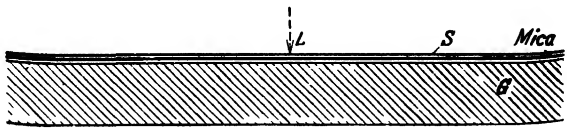


FIG. 135. ELIMINATION OF THE HALO BY USING A VERY THIN TRANSPARENT SCREEN CARRIER SEPARATED FROM THE BOWL OF THE BULB

long as there is no contact, since no ray entering the glass can reach the critical angle. The arrangement of Fig. 135 is also free from light halos.

The method mostly used to-day for reducing the halo disturbance consists in not fusing the fluorescent material deeply into the glass bulb, but attaching it where possible to the surface. The surface of a fluorescent particle which has contact with the glass wall—and therefore contributes to the formation of a halo—is then relatively small compared with the surface radiating outwards, so that the halo becomes correspondingly less intense. Fig. 136 (*a*) shows the path of a ray emanating from a fluorescent particle half embedded into the glass bowl with the formation of a bright halo due to total reflection. Fig. 136 (*b*) shows the particle just touching the glass wall only. A much larger proportion of radiation becomes available for useful external observation, and only a small portion emanating from the point of contact between the particle and the glass gives rise to a feeble halo.

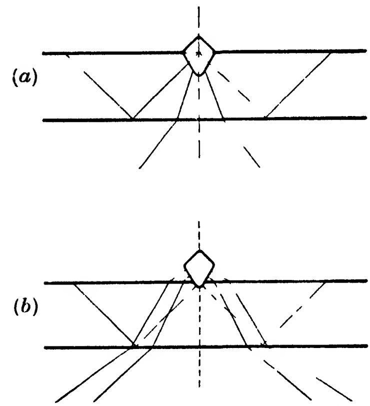


FIG. 136. PATHS OF THE RAYS AND FORMATION OF WEAK HALOS BY FLUORESCENT PARTICLES ON THE SURFACE OF THE GLASS

Another method of avoiding halos consists in making the screen transparent. In this way, the light rays reflected from the exterior surface of separation between the glass and the air either pass through the screen or become totally reflected. In the latter case, if the index of refraction of the screen is suitable, repeated total internal reflection will occur and no luminous anomaly directed outwards can be seen.

Unfortunately, transparent screens which are efficient are not known nor are they predicted.

The difficulties described do not occur or, at any rate, are easily avoided with screens which are viewed from the front.

2. **Practical Types.** The first sealed-off hot cathode tubes with low electron velocity take us back to the time of Wehnelt and Westphal. These were employed mainly for demonstrations and less frequently for practical purposes. Very low illumination of the spot and frequently bad focusing, together with a heating current of 10 amperes, were great drawbacks to the general adoption of tubes of this type. The outstanding technical characteristics of the first hot cathode tubes were a platinum strip cathode carrying an oxide spot, the absence of preliminary focusing, the formation of a beam by means of a diaphragm, and the presence of small quantities of gas remaining in the tube. The tubes were operated with low anode potentials of several hundred volts, and the resulting energy of the rays was so low that the fluorescent pattern could only be observed in completely darkened rooms. The first tube to attain popularity in practice was the Western Electric model, developed by Johnson.[66] In this pattern which to-day is still almost unaltered after more than ten years—Fig. 137 shows the most recent construction of Johnson's tube—most of the important features of various modern constructions are embodied. The fluorescent screen is fixed directly on to the slightly curved glass bowl of the bulb. The various supply leads are

FIG. 137. GAS-FILLED CATHODE-RAY TUBE (*Western Electric Co.*)

taken to a pin base. The American tube is filled with argon at a pressure of 5×10^{-3} mm. Hg for the purpose of gas-focusing. The special features of the tube are the construction of the cathode already discussed and the mounting of the electrode assembly, including the deflection system, on a glass pinch. In order to reduce the number of leads through the pinch, one deflection plate of each pair is connected to the anode, a procedure which excludes the use of the tube for some operations and measurements: for instance, circuits in which separate pole connexion to the generator for the ordinate and abscissa plates in order to produce variations and reversals, and also those cases in which the pairs of deflection plates must be biased with respect to the anode, are excluded.

As distinct from the older type of American tube with small tubular anode, there is in the latest type shown in Fig. 137 a circular electrode whose diameter is only slightly smaller than that of the glass neck and which is connected to the tubular anode. This alteration in construction of the anode considerably reduces origin distortion which was particularly pronounced in the older form of tubular anode. The electrons returning from the screen are no longer almost completely taken up by the deflector plates as in the older type of construction, but by the anode which has ample penetrance on the space in front of the fluorescent screen. The reduced deflection plate current leads to a corresponding reduction of the loading on any source of potential to which the deflection plates may be connected. In spite of the elegant cathode construction, already explained above, by means of which bombardment of the cathode by ions is reduced, the anode voltage of the American tube must not be increased above 400–500 volts, otherwise the life of the cathode will be reduced considerably. Anode voltages for practical purposes lie between 200–350 volts. When zinc silicate or sulphide screens are used, the tubes give a green fluorescent spot which is brilliant considering the colour of the spot and the low anode voltage employed. Having regard to the low anode voltage and the very appreciable afterglow of the screen material, these tubes are not suitable for photographic recording of non-recurrent phenomena or for observations in a rotating mirror. On the other hand, they are excellent for standing figures. The special advantages of this type of tube, or any cathode-ray tubes operating on low-electron velocities (200 volts) are the high deflectional sensitivity

and the possibility of working from d.c. mains or batteries. These properties make the low anode voltage tubes appear worthy of particular recommendation for use in schools, experimental work and directional measurements.

The low-voltage tube recently produced by the A.E.G., as shown in Fig. 138, on a stand, has properties very similar to the American tube already discussed.

An advantageous departure in design from the American tube is that each deflection plate is taken out at the side with the result that the limitations mentioned above are avoided,

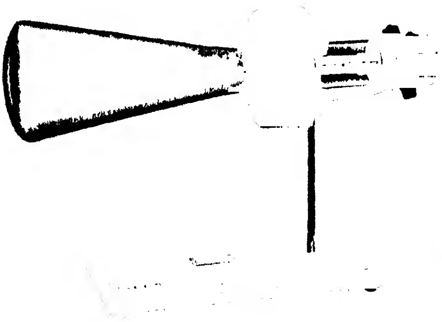


FIG. 138. GAS-FILLED CATHODE-RAY TUBE (*A.E.G.*)

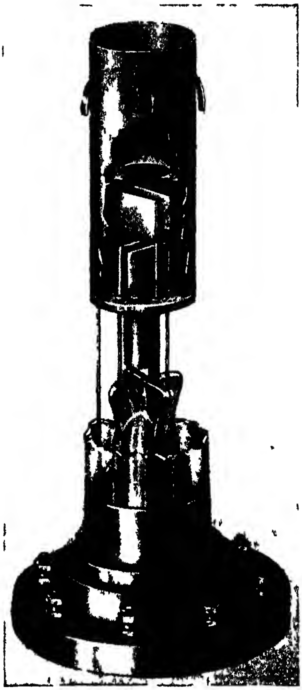


FIG. 139. GAS-FILLED CATHODE-RAY TUBE (*Cossor*)

the low capacitance makes the measurement of high-frequency phenomena easier, and reduces intercoupling of any such circuits connected to both pairs of plates. Another important type of tube, the construction of which resembles very much the system shown in Fig. 137, is shown in Fig. 139. This English tube made by Cossor has one peculiarity. Connected directly to the anode is a large metallic cylinder which envelops the deflection plates. This enlargement of the anode surface and the fact that a considerable portion of the cylinder occupies the space between the fluorescent screen and the deflecting plates, reduces still further the stream of electrons to the deflecting plates. The considerable decrease in the current

flowing to the deflection plates as a result of the introduction of the internal cylinder, is indicated by the measurements reproduced in Fig. 140. The current flowing to the deflection plates in the ranges which are of importance in the loading of the tube, is reduced to about one-tenth by the internal cylinder or similar electrode whose influence on the screen zone results in a high value of D. In gas-filled tubes having such trap electrodes, coupling resistances up to 10^6 ohms can be used without appreciably affecting the deflection characteristic. Also the + shaped pinch which carries the whole electrode system of

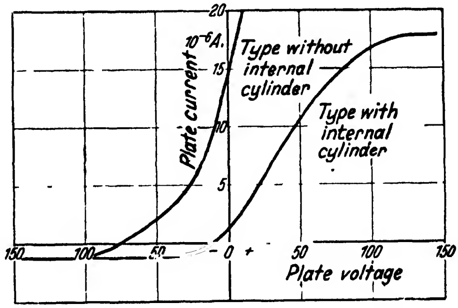


FIG. 140. PLATE CURRENT CHARACTERISTICS OF TUBES WITH AND WITHOUT THE INTERNAL CYLINDER SURROUNDING THE DEFLECTION PLATES

this tube is worthy of mention. The operation of gas-filled cathode-ray tubes with hot cathodes at higher anode voltages, i.e. 1 000–3 000 volts, consistent with satisfactory life of such cathodes, was first made possible by the author's tube shown in Fig. 141. A notable feature of this tube lies in the simultaneous use of gas-focusing, a point cathode, and a Wehnelt cylinder. The negatively biased cylinder enclosing or surrounding the cathode not only brings about preliminary focusing, but also keeps a good proportion of the gas ions away from the cathode as stated previously. The reduction of cathode bombardment brought about by the Wehnelt cylinder which, with high anode voltages, may be several hundred volts negative to the cathode, first made the use of such high anode voltages possible and, in spite of the limited efficiency of the ordinary cathode, was responsible for the formation of a brilliant spot. Raising the anode voltage to 1–2 000 volts increases the light output 50 per cent compared with the low

voltage tubes of equal ray current. This difference, which is far greater than the corresponding increase in anode load, is explained by the fact that the efficiency of the screen depends on the voltage.[67]

The increase by 50 per cent of the light output has proved much more important than the decrease in deflectional sensitivity, which is about one-seventh in the case of electrostatic, or one-third in the case of magnetic deflection. Further, the large surface anode which takes up the return stream of electrons from the screen more effectively became recognized through the system shown in Fig. 113, and has been adopted

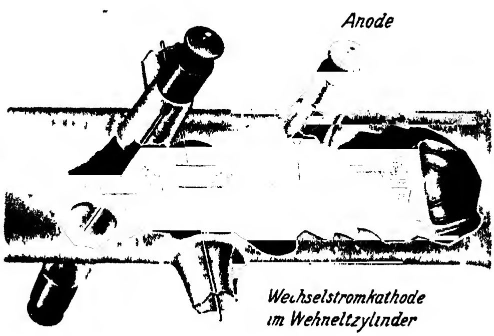


FIG. 141. ELECTRODE SYSTEM OF THE AUTHOR'S OLD GAS-FILLED TUBE

in many cases. An almost point-shaped emitting wire cathode is used in the tube, and the magnetic field due to the current carrying wire is balanced out; consequently, heating by a.c. is possible. In this type of tube the deflection plates are each taken out separately by means of glass side tubes. The tube contains argon at a pressure of 5×10^{-3} mm. Hg. It has a very fine grained and perfectly even screen of special material fused into the bowl of the glass bulb.

For problems where only low anode voltages (up to 2 000 volts) or very low deflection voltages are available, this type of tube has been superseded recently by a construction in addition to the high-vacuum forms illustrated further on, which has a simple accelerating lens instead of an anode. Both forms of construction contain indirectly heated oxide cathodes. The form used in gas-filled tubes has been illustrated already and discussed above. These tubes contained argon at a pressure of

about 5×10^{-4} mm. Hg. In the form in which the deflection system has no zero error, the latter fault, which is very small at this gas pressure, is entirely eliminated. As distinct from the older types of tube for measuring purposes, a relatively large screen 18 cm. is employed in this tube. The deflection plates here again are taken out sideways. Gas-filled tubes as a rule give sharp spots and accurate measurements are possible

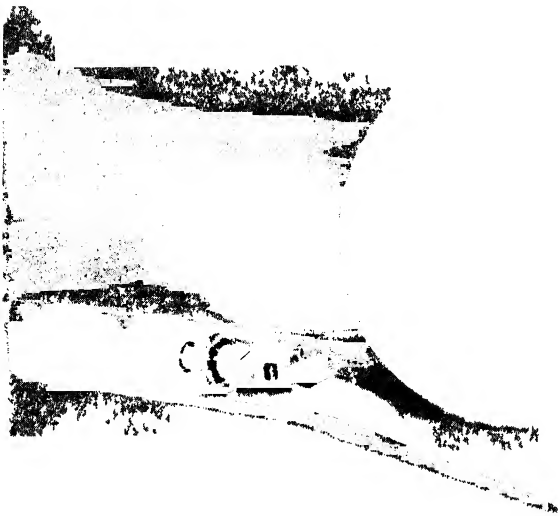


FIG. 142 R.C.A. RADIOTRON CO., HARRISON, NEW YORK. ASSEMBLY AND BULB DIMENSIONS OF VARIOUS HIGH-VACUUM TUBES

when the deflection plates not in use are left free. On the other hand, in the case of high-vacuum tubes, it is essential that deflecting electrodes not in use should be connected to the anode either directly or through a non-inductive resistance, if possible not higher than 5×10^6 ohms. Fig. 142 shows a small high-vacuum tube which was put on the market in 1933 by R.C.A.-Radiotron. The system, which in common with the deflecting plates is mounted on a base, has the usual electron-optical ray path, discussed in detail previously. The distance of the image in the small tube is only about 16 cm., the screen diameter about 7 cm. The illustration shows the comparative size of the screen of a large tube by the same firm. In the model illustrated, one of each set of deflection plates is

connected directly to the anode, so that it is not possible in this case to arrange a symmetrical disposition of the deflecting voltages. Fig. 143 illustrates the assembly of a Cossor high-vacuum tube for measuring purposes. The special features of this tube which, in its electron-optical construction, departs somewhat from the other high-vacuum tubes discussed in this book are these: a small point cathode is used and this is projected directly on to the screen; modulation does not affect the position of the spot in spite of the direct projection of the cathode, because the latter and its virtual image due to the first lens system lie very near to the first anode, and a very small Wehnelt cylinder serves as an electrode for brightness control. The system contains one more accelerating stage than is usual at the present time. Another voltage tapping is therefore taken from the divider fed from the mains equipment. All four deflecting plates are taken out separately through the pinch.

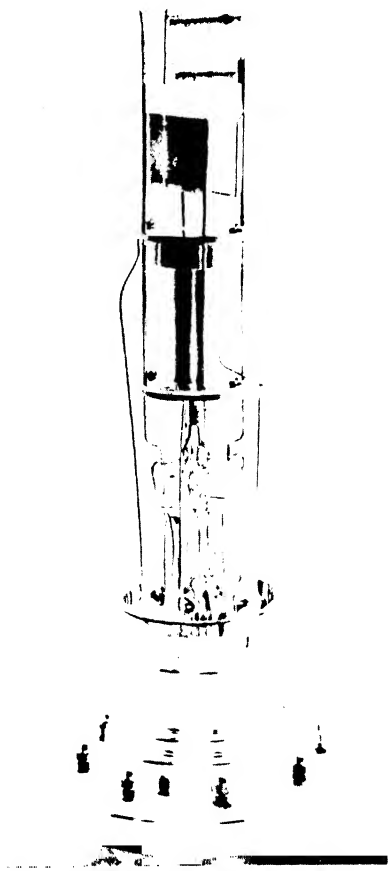


Fig. 143. Cossor (London) System of High-vacuum Cathode-ray Tubes

Another high-vacuum tube for making measurements which can be operated at anode voltages up to 4 000 and 5 000 is shown in Fig. 144. The fact that the sharpness of the spot and the deflectional sensitivity are independent of the frequency of the deflection voltages, a relation which holds good down to the ultra short-wave range, seems to make the high-vacuum tube eminently suitable for carrying out all kinds

of high-frequency measurements. On account of its use in the h.f. range and in order to secure a simple construction for measuring purposes, the deflection plates are taken straight out at the side. The screen of this type also has a diameter of

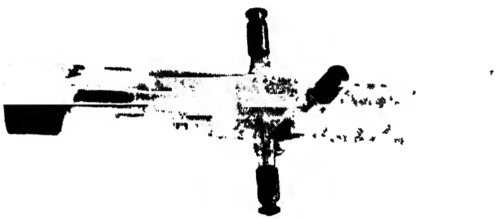


FIG. 144. HIGH-VACUUM MEASURING TUBE WITH DEFLECTION PLATES TAKEN OUT AT THE SIDE (*Leybold and von Ardenne*)

18 cm. and is composed of material No. 2, the characteristics of which were given in detail by measurements, in the section on fluorescent screens. At anode voltages of 3 000–4 000 volts

FIG. 145. HIGH-VACUUM TELEVISION TUBE (TAKEN WITHOUT METALLIZING) WITH 30 CM. SCREEN FOR 18 × 22 CM. PICTURE IN BLACK AND WHITE (*Leybold and von Ardenne*)

the tracing speeds attained with this type of tube are sufficient to record all frequencies in the l.f. range and even some of the medium frequencies. Fig. 145 illustrates another high-vacuum tube with a particularly large bulb. This is fitted with one

or two pairs of plates according as magnetic or electrostatic deflection in the vertical direction is to be employed. The standard bulb size for home television might have a screen diameter of about 25 cm. The anode current and brightness intensity characteristics of the high-vacuum tubes in Figs. 144 and 145, which were developed by the author, have already been given in another part of this book.

Besides the standard types mentioned there is a large number of special ones which are discussed in the following sections, in so far as they are of practical importance.

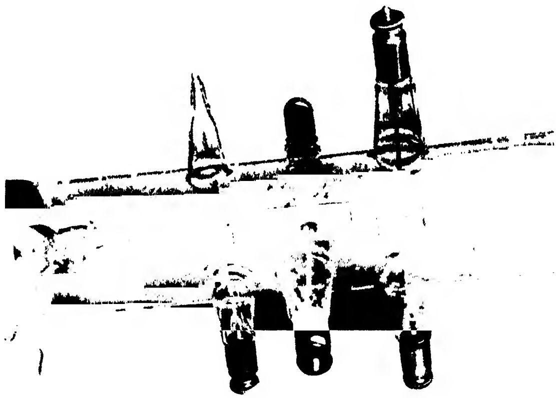


FIG. 146. DEFLECTING SYSTEM WITH PAIRS OF PLATES OF DIFFERENT SENSITIVITY IN AN OLD GAS-FILLED TUBE USED IN PARTICULAR FOR SMALL ANGLES OF DEFLECTION

3. **Types for Special Purposes.** At first, mention will be made of types which have been constructed and which differ from the standard forms by special deflecting systems. It is now nearly standard practice to make both pairs of plates the same, or nearly so, in order that equality of sensitivity may result. Equality of sensitivity is unimportant in many cases; it is more important that at least one pair of plates has as great a sensitivity as possible.

When measurements are to be made with one pair of plates only or when, for instance, a voltage of large amplitude for time deflection is available, it is expedient to make one pair of plates more sensitive than the other. Such a deflection system with unequal pairs of plates is shown in Fig. 146. Fig. 147

shows a deflection system with which three different sensitivities in the one direction can be secured. Instead of one pair of plates there are two arranged in the same direction, and having their lengths in the ratio 1 : 2. Connecting the shorter pair to the voltage to be measured gives the lowest sensitivity. The longer pair gives medium sensitivity and both together give the highest sensitivity. The distance between the plates

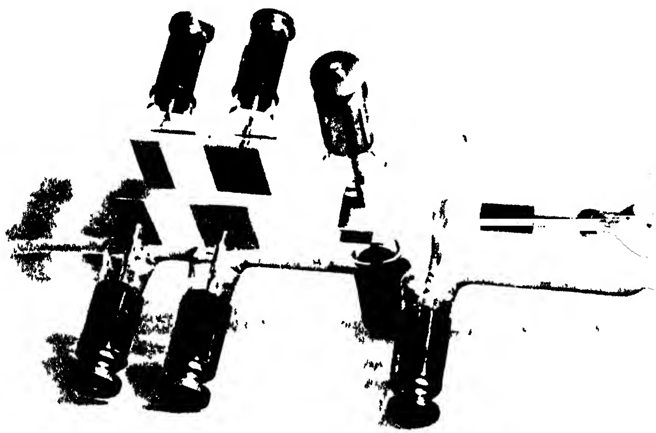


FIG. 147. PLATE SYSTEM OF THREE DIFFERENT SENSITIVITIES FOR USE WITH HIGH VOLTAGES

in the type illustrated is much greater than usual, and is for measurements in the 100–1 000 volt range.

When gas is present there is some danger of the high deflecting voltages producing a discharge in the deflecting system. In the high-vacuum tube conditions are much safer, though in this case care should be taken when employing such high voltages that these are conducted to the parallel plates symmetrically. Fig. 148 shows a special shaped bulb neck which has been used frequently recently in combination with high-vacuum systems. In this case the neck of the tube is narrowed down considerably over a distance of about 8 cm., so that the external control electrodes or deflection coils, which may or may not have iron cores, can be brought as close to the ray as possible, and on this account secure a high sensitivity. As a result of the constriction of the neck the penetrance of the

anode with respect to the screen zone is relatively small, and there is a danger that troublesome wall charges may be produced. The inside of the bulb should therefore be metallized

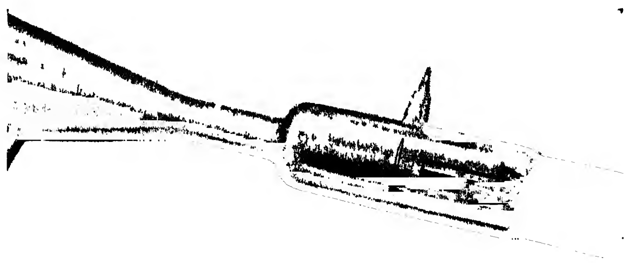


FIG. 148. SPECIAL FORM OF GLASS NECK FOR EXTERNAL ELECTROSTATIC OR MAGNETIC CONTROL

and connected electrically to the anode when a bulb shape of this kind is used in connexion with high-vacuum systems.

Figs. 149 and 150 give particulars of the construction of the

FIG. 149. FORM OF COIL SUPPORT FOR MAGNETIC DEFLECTION

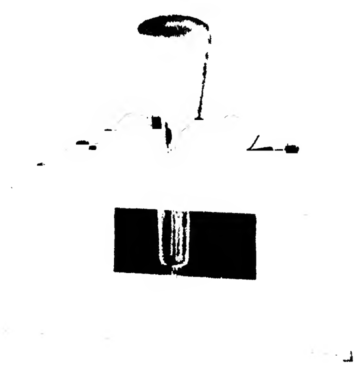


FIG. 150. COIL SUPPORTS FOR MAGNETIC DEFLECTION IN TWO CO-ORDINATE DIRECTIONS

supports for the coils for magnetic deflection. Fig. 150 shows a good arrangement for simultaneous magnetic deflection in

both directions. An important special type in which the time of passage of the electrons is compensated for measurements in the short- and ultra-short-wave range is shown in Fig. 151.

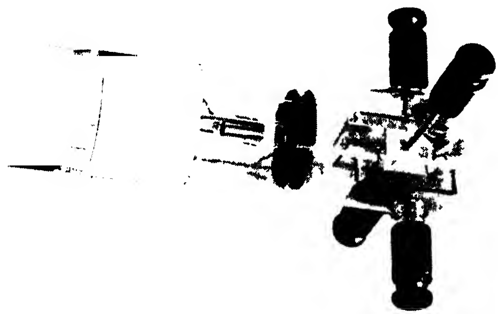


Fig. 151. Tubes for Making Measurements at High Frequencies
(*H. E. Hollmann*)

Experiments with this electrode, which is due to Hollmann, have shown that it can be operated with considerable success without perceptible phase errors even at wavelengths of the

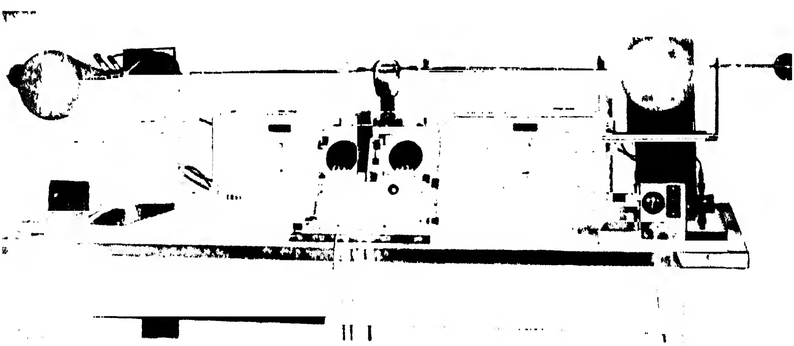


Fig. 152. Equal Phased Deflection with an Oscillation of 80 cm. Wavelength
Hollmann's deflection system (*left*), ordinary deflection system (*right*)

order of 1 m. An experimental arrangement photographed in operation confirms this, and is shown in Fig. 152. The illustration shows a transmitter for 80 cm. wavelength. In both cathode-ray tubes on the right- and left-hand sides of the

transmitter the deflection plates are connected by a Lecher wire, each two being connected to obtain deflection in the same phase. The left-hand tube having the deflecting system

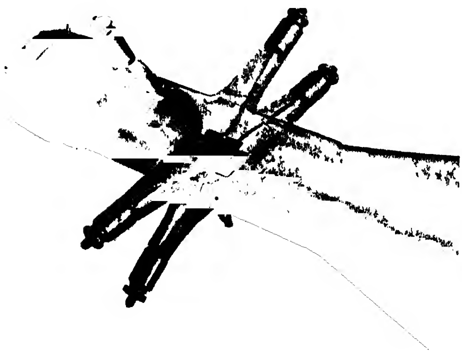


FIG. 153. SYSTEM WITH CONDENSER DEFLECTING PLATES

described, the phase relations are shown correctly by the registration of a line on the fluorescent screen. On the other side, with a tube having a standard deflecting system, the pattern on the screen is seen to be an ellipse. With this special type of tube, therefore, phase measurements in the extreme

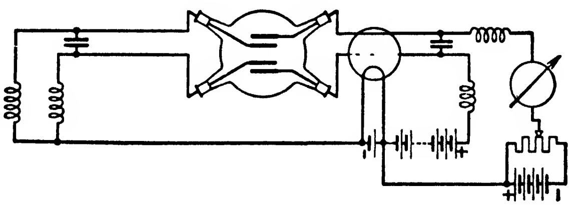


FIG. 154. LECHER SYSTEM WITH TUBE HAVING CONDENSER PLATES

frequency range are possible, as are also amplitude measurements, if the extent of the decrease in sensitivity which occurs at the frequency of operation is taken from Fig. 95, or is calculated from the equation on which this figure is based.

For high-frequency measurements, leading out the deflection plates at the side of the tube is essential in order to keep down the distributed capacitance and self-inductance to a low limit

(i.e. resonant frequency of deflecting system corresponding to a wavelength of 10–20 cm.).

Fig. 154 shows another special type for the ultra-short-wave range. This deflecting system has two plates each of which is led out as a condenser. Therefore, as shown in Fig. 154, the tube can be introduced directly into the Lecher system of a short-wave transmitter without causing any disturbance. If the tube is properly connected, it will indicate only high-frequency voltages in spite of the high d.c. voltage between the Lecher

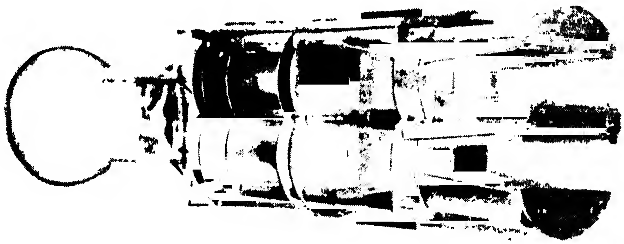


FIG. 155. CONSTRUCTION OF AN OLD FORM OF DOUBLE CATHODE-RAY SYSTEM

wires. This tube, by H. E. Hollmann, is specially for measuring voltages in Lecher systems.

In order to obtain abnormally high sensitivity to deflection, i.e. to have very low electron velocities in the deflecting space without affecting the brightness and sharpness of the spot, tubes in which the production of the ray and the preliminary focusing take place at high velocity have been developed, and the electrons are then retarded to a speed corresponding to a voltage of 100 in an area where the field is, as far as possible, uniform.

After traversing the deflecting space, the subsequent acceleration at anode potentials of several thousand volts takes place. The advantage of ray formation and preliminary focusing at higher anode voltages is that focusing is more complete and the losses by spreading in the gas are much lower. The deflectional sensitivity of the cathode-ray tube with retarding field has been increased to about 10–20 times that of normal tubes. Another device which was produced in the author's laboratory in 1930, and which has since been developed in improved forms

with high-vacuum systems, is shown in Fig. 155. The idea of having two cathode rays for making two measurements is very old (Kock). The main difficulty is in the mutual interference between the electrode systems. This can be reduced by introducing a screen between the systems of the arrangement shown in Fig. 155. In modern types of double cathode-ray tubes, high-vacuum systems or ones having electrostatic accelerating "lenses" at reduced gas pressure are employed. The voltages for the main anode—the lens electrode—as well as that for operating the indirectly heated cathodes, are the same for systems of similar construction, so that the same corresponding connexions exist internally. In this way, a very considerable reduction can be made in the number of connexions and leads through the pinch. Besides the pair of plates for making comparative measurements, a further pair common to both systems is usually provided for time deflection.(70)

Fig. 156 illustrates a special high-vacuum tube of compact construction designed specially for projection work. In this case the distance of the image is only about one-third that of a normal high-vacuum tube, consequently the spot diameter is also reduced to about one-third. A high power lens of 8–10 cm. focal length permits the projection of oscillograms or pictures on to large-sized screens. If full advantage is to be taken of a sharp spot, the condenser lens must be adequately corrected. For simple demonstrations, a condenser (power $F/1$), which has not been corrected chromatically, and illustrated in Fig. 156, is sufficient, especially if the screen material used is one which has a narrow spectral sensitivity band.

An interesting application is that in which the cathode-ray tube is used as a switch or relay of low time lag. The fundamental idea, which is well known, is to employ the current produced when the cathode ray strikes a guard ring for the control or starting of some particular operation. In principle, one or more electrodes can be provided. They are arranged at various points at the bottom of the bulb according to the function the tube is required to perform. Arrangements in which one or more trap electrodes are fitted on one deflection axis, or a large number of them in a circle round the centre of the fluorescent screen, are of considerable importance. The trap electrode circuit has a current flowing to it only when the ray impinges upon it. The current must cease immediately the position of the ray is changed when it no longer strikes the

trap electrode, a condition which can only be fulfilled when the latter is fixed in a certain position. If the trap electrodes are arranged at the bottom of the bulb so that they are free on all sides, it is clear that some current will flow to them even when the ray does not impinge upon them. The current is almost independent of the position of the ray. This result, which at first appears surprising, is explained by the fact that the secondary electrons at the bottom of the bulb or at the

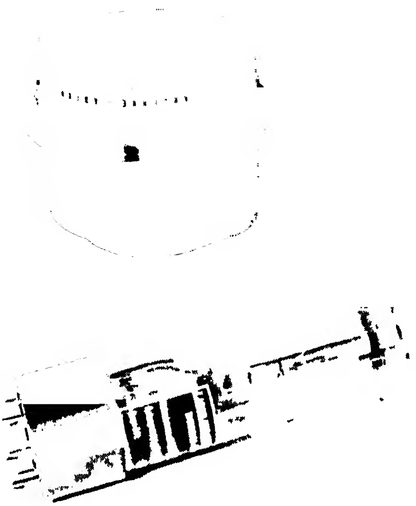


FIG. 156. A HIGH-POWER LENS AND A SHORTENED HIGH-VACUUM TUBE FOR PROJECTION PURPOSE (*Leybold and von Ardenne*)

fluorescent screen do not return to the anode, but to the trap electrode which is nearer and practically at anode potential. A neat circuit can be secured in gas-filled tubes also by means of the electron ray when care is taken to see that the stray electrons are conducted away immediately by arranging metal surfaces connected to the anode near or behind the trap electrode. The condition referred to can be fulfilled even more simply and successfully if the trap electrodes are towards the bottom of the bulb, and insulated from the side by glass and screened. Fig. 157 shows an old experimental tube with guard rings which are screened by glass. Screening behind ensures that the return stream of electrons from the bottom of the bulb to the anode does not strike the electrode, and

that current of any magnitude only flows when the cathode ray strikes the electrode. This arrangement is not entirely free from inertia. During each operation the ray must impinge on the trap electrode long enough for the electrons to charge it, or to discharge it through an externally connected resistance. The greater the capacitance of the trap electrode and the external conductor connected to it, the greater will be the inertia of the electron ray switch. By using a particularly prolific source of rays, giving a current of more than 1 mA., with an electron optical system designed to suit the conditions

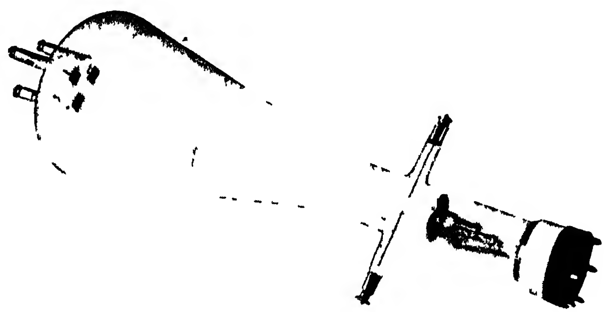


FIG. 157. OLD FORM OF EXPERIMENTAL ELECTRON-RAY SWITCH

of operation, the author succeeded in reducing the time lag of this switch to 10^{-5} second. Consequently, it is preferable to all mechanical contrivances. R. A. Watson Watt has an interesting use for the trap electrode principle.[68] He arranges a trap electrode sideways on the abscissa axis, and by a suitable switching arrangement ensures that the ray impinges on the trap electrode when in the stationary position. As soon as deflection in the ordinate direction occurs, due, for example, to a single potential impulse, the ray current flow to the trap electrode is interrupted and a single time sweep occurs, this itself being cut off automatically by the process at the end of its stroke. A tube similar to that of Watson Watt is shown diagrammatically in Fig. 158. The voltage drop at the resistance, which is about 3×10^6 ohms, caused by the ray current, is of the order of 10 volts. The time lag in constructions of low capacitance is of the order of 10^{-3} to 10^{-4} sec. when normal gas-filled tubes and ray currents are used.

The time constants can be reduced to the order of 0·1 or 0·01 of their former value by using smaller resistances which may necessitate the introduction of amplifiers. The effective current

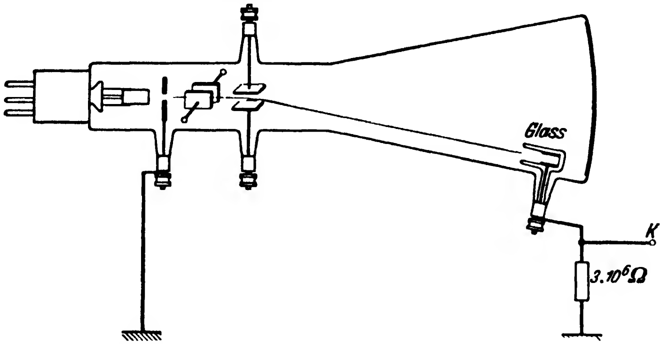


FIG. 158. SPECIAL TUBE WITH TRAP ELECTRODE FOR USE WITH A SINGLE SWEEP

at the screen end of the ray can be measured by means of the trap electrode arrangement indicated. Fig. 159 shows another interesting special tube having trap electrodes.

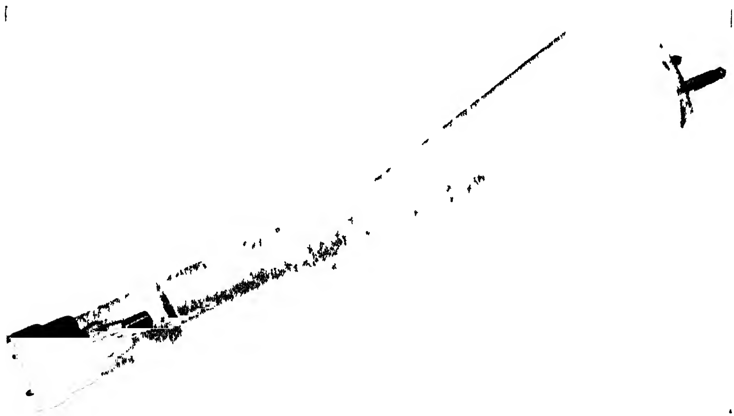


FIG. 159. COMPASS TUBE (*Watson Watt*)

At the bottom of the bulb of this tube are two semi-circular metal plates which have a thin fluorescent layer to facilitate observation of the ray. Both plates are led out separately. This tube, inspired by R. A. Watson Watt, is intended for

the construction of an automatic directional indicator or a self-operating control compass free from inertia. The tube is operated in such a way that the fluorescent spot or stroke lies in the space between the two semi-circular trap electrodes.[68] Every position in which the ray is deflected is recorded by a bridge circuit and amplifier, and can be used for all kinds of control, as, for instance, in rotating the cathode-ray tube with the aid of mechanical devices.

In this tube a current should only flow when the rays strike the corresponding trap electrode. In this connexion it was found necessary to place a mica plate in the slot between the deflection plates of the tube illustrated. This mica plate extends to the bottom of the bulb.

Electrode arrangements similar to those in the electron ray switch have frequently been suggested for carrying out frequency multiplication.

A large number of very practical cathode-ray tubes of special construction, some of which are extensively used, has been evolved for sound-film recording. These tubes are discussed at the end of the book in the chapter dealing with the cathode-ray tube as an operating device.

4. **Manufacture and Testing.** As glass is the principal material used in the construction of sealed-off cathode-ray tubes, glass technique and the work involved in preparatory glasswork constitute a great part of the manufacture of the tube.

The construction of the tube starts with the glass bulb and its production, and attention must be paid to quality and freedom from strain in the glass used, to prevent cracking and bursting during evacuation on the pump or on a subsequent occasion. This applies particularly to the large bulb of the television tube. The bulb is best blown in a mould and embraces the conical part of the tube with the screen surface and cylindrical extension which subsequently carries the lead-in for the electrodes and at its open end the filament lead-in wires. Special care must be taken to see that the glass wall which is to act as screen carrier is made evenly and free from striations. Special attention must be paid to the extent of the curvature of the bowl of the bulb which should be kept small in order to secure undistorted screen images. In order that the bulb shall be able to withstand the external atmospheric pressure, particularly during the critical heating process, the radius of curvature

must not be made too great. Illustrations of completed tubes show clearly the extent of the bulb curvature which has been decided by the result of practical experience. If the fluorescent screen is burnt into the bulb after the fusing process, the glass bulb should be obtained from the glass works with slightly less curvature, as this increases markedly during the fusion process. The most complicated and important electrode connexion to

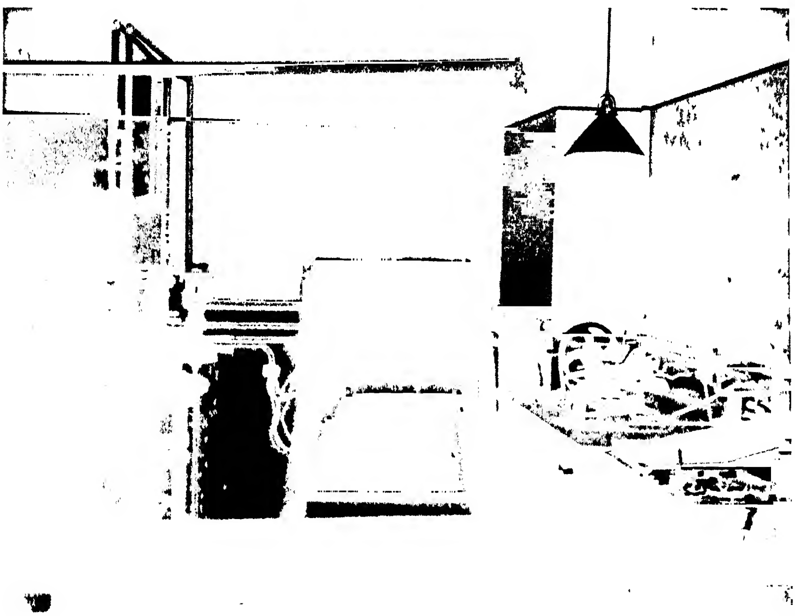


FIG. 160. EQUIPMENT FOR MAKING GLASS FOOT

the tube is the pinch which carries the lead-in to the filament, the supports and voltage leads to the focusing electrode, and possibly also the anode and the plates. During manufacture, leaks can easily occur at the lead-in joints, and cracks develop subsequently. Consequently, each operation and subsequent heat treatment must be carefully supervised.

The original form of the pinch is that of a glass tube flattened out at one end by means of a so-called flanging machine. The supports are sealed into this tube in the position corresponding to the subsequent mounting of the electrodes. While the glass and electrodes are being heated simultaneously, a pair of pincers

or multiple-head pinch-making machine is used to flatten the glass into a pinch so that the leading-in wires are in one plane.

Care must be taken to avoid leaving air bubbles on the platinum-covered wires embedded in the glass. Furthermore, the platinum-covered wires must be carefully inspected to detect microscopically minute longitudinal cracks which would permit air to reach the interior of the tube. In order to free the pinch from strain and to avoid cracks appearing later, it must be placed in an oven after manufacture, where it cools gradually and removes strain. On account of its ease in working, lead glass is generally used in making the pinch.

Fig. 160 shows the apparatus necessary for making the pinch: on the left the pinch-making machine, in the centre the annealing oven, and on the right the flanging machine. If the deflection plates are to be led out direct at the side, glass pips must be blown in the bulb at suitable places. The lead-in wires should be covered with fused glass in an oxygen flame, and the entire structure with its glass coating sealed on to the terminal of the bulb. Here again careful annealing is essential to avoid subsequent cracking.

After the preliminary glass work is completed, the electrodes should be prepared in their requisite geometrical form. They should either not be touched by hand at all, or only when the hands have been carefully washed in ether or petrol. Otherwise minute traces of grease are left on the electrodes and result in objectionable emanation of gas from the electrode when the tube is in operation.

In any case it is worth while washing the electrodes with dilute nitric acid, caustic potash, benzine, and finally carbon tetrachloride just before mounting. This is particularly important in the case of high-vacuum tubes. The equipment necessary for the manufacture of the electrodes and the cathode is shown in Fig. 161; on the left, the tools and the stereoscopic lens necessary for the examination and investigation of small electrodes and in the foreground two spot-welding machines. When the electrodes which have already been mounted are actually fitted into the bulb, the individual components must be arranged according to the design of the particular tube by means of the necessary adjusting tools, and accurately positioned with respect to one another and symmetrically to the axis of the tube. The tube finished off in the manner described is then put on the pumping machine preceded by a

liquid air trap. After continuous control of the vacuum has shown that there are no leaks of any kind in the tube, the latter is placed in an oven and heated for several hours at 400° C. to remove the film of moisture on the walls. Sometimes leaks which have very small dimensions are present and they are

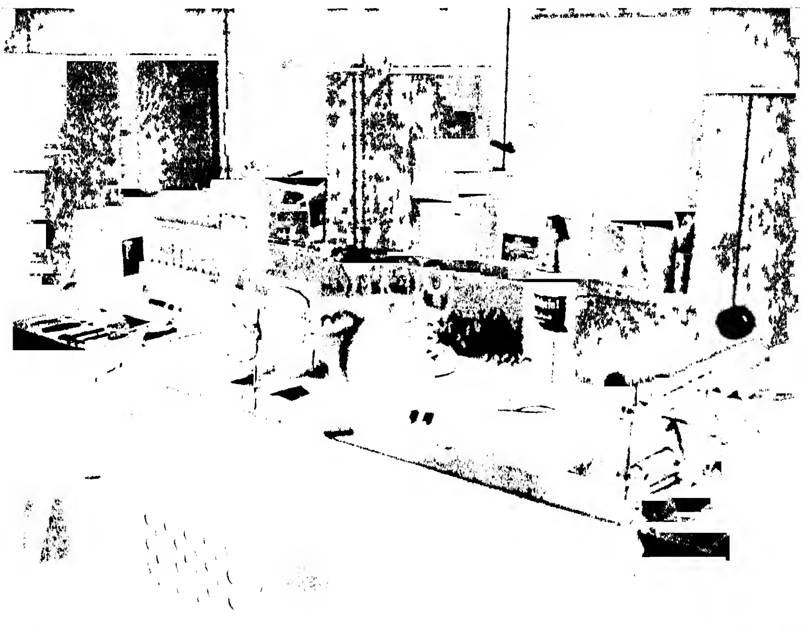


FIG. 161. SPOT WELDING MACHINES AND EQUIPMENT FOR MAKING ELECTRODES

extremely difficult to detect. Consequently, special devices must be used to find them quickly. A simple method of finding leaks is the colour change which occurs in a glow discharge in the presence of alcohol vapour. If successive applications of alcohol are made to the surface of the bulb, a colour change occurs immediately the discharge, which has been maintained in the tube, reaches the leak which is moistened with alcohol vapour. Another method used, particularly for the pinch and terminals, is that in which the terminal wire is dipped in colouring matter. The external pressure forces the colouring along the terminals into the tube, and the point at which leakage is taking place can be recognized immediately the

colouring reaches it. Heating and cooling of the tube must be done slowly to avoid producing additional strain in the glass and cracks which may result therefrom. Those electrodes which reach high temperatures during operation of the tube must be heated up to a high temperature before the bulb is sealed off. With hot cathodes this is done by heating the cathode for a short time at a temperature which is slightly higher than normal. Electrodes which become warm during the operation of the tube are preheated by electron bombardment, or by eddy currents produced by a high-frequency oscillator with an output of about 1 kW.

Immediately after the preliminary heating process, the cathode should be heated for some time, at first without

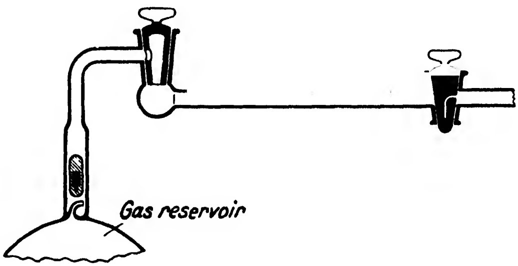


FIG. 162. CONSTRUCTION OF A GAS COCK

accelerating field. Finally, during the latter half of the pumping period, the forming process of the cathode takes place according to the methods previously stated. In gas-filled tubes, only gas which is spectroscopically pure should, in principle, be used for filling. For economy, the filling can be done effectively through a special tube (see Fig. 162). This tube is closed by two cocks, one of which doses out small quantities of gas through a hole bored in one side. The exact operating pressure is attained by pumping out the excess of gas in several stages. The tube after being completely evacuated, and then filled with gas, is taken off the pumping tube in the same way as is usual with amplifying valves as soon as it shows itself to be operating satisfactorily. Fig. 163 shows a simple pump for making experimental tubes, the quartz diffusion pump, a partly finished tube, and a gas bottle under the raised oven being visible. On the left-hand side of the illustration is an eddy current heating set with its heating coil.

The sealed-off tube is cemented into a base according to the purpose for which it is to be used. For very high anode voltages it is advisable to fill the base with insulating material to avoid leakage. The tube when capped must be operated at normal anode voltage for at least an hour before it is finally

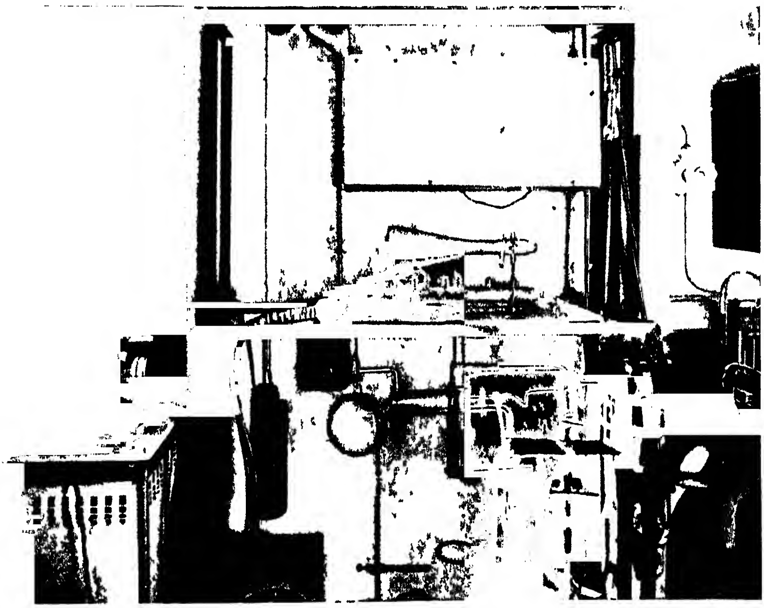


FIG. 163 SIMPLE PUMPING MACHINE WITH OVEN

ready for use in measuring circuits. During this period leaks or other faults will make their appearance.

During and after manufacture the sharpness of the spot must be adjusted, not only in the undeflected position, but preferably at all points which it is likely to take up over the surface of the screen. For this test, either an arrangement similar to that which produces a television scan or the much simpler arrangement of a circle tracing bridge, previously referred to, can be used. Non-symmetrical features in the fluorescent spot become noticeable in the tracing of the circle through corresponding differences in sharpness of the line of the circle. By the aid of a potentiometer the voltage fed to the circle tracing bridge can be gradually increased with the

result that the spot traces out circles of ever-increasing diameter. Fig. 164 shows a circuit for testing spot sharpness and brightness control. Besides testing by means of the circuit of Fig. 164, the testing of the stationary spot must not be overlooked, since defects such as formation of corona, distortion, etc., in the stationary spot can be easily seen. A probable defect in the stationary spot is more easily discovered by a.c. heating than by circle tracing. The tracing bridge must, of course, be altered for testing high-vacuum tubes in such a way that a symmetrical arrangement of voltage is obtained. For more exact control of the properties of the tube, the tracing of the anode current characteristic as well as the independent tracing of the brightness characteristic are carried out effectively on a television scan (raster), the limits of spot sharpness being controlled at the same time. When testing and forming an opinion about cathode-ray tubes, it is important to note the actual number of working hours of the oscillograph. This can be done very conveniently by some device fed from a.c. mains. Parallel connexion to a synchronous clock circuit is all that is required. Small meters operated by batteries are equally as good. When feeding from batteries, the mean cathode current has to be considered in order to obtain the number of hours of operation from the number of ampere-hours shown by the meter.

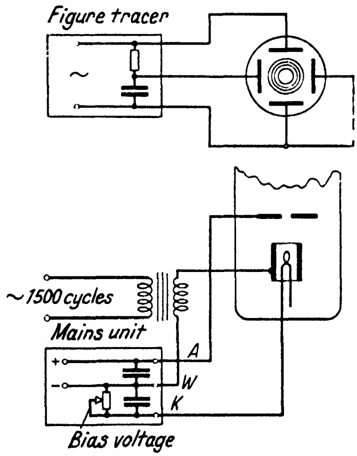


FIG. 164. CIRCUIT FOR TESTING THE SHARPNESS OF THE SPOT AND FAULTS IN BRIGHTNESS CONTROL

VI. PRECISION OF MEASUREMENT WITH CATHODE-RAY TUBES

In previous sections it has been stated in every instance how precision of measurement of the cathode-ray tube is affected by its construction and limitations which are imposed by the circuit in which it is used. In consequence, details of

errors likely to occur will not be considered exhaustively in this section, but a short list of references to the previous sections will be given so that the reader can make himself familiar with the errors of measurement which are likely to occur.[69] A number of inaccuracies result from the physical conditions under which the oscillograph tube is operated. The internal and external zero error in the gas-filled tube belong to this category as does also the way in which the sensitivity of the control electrodes depends on frequency (see sections on electrostatic influence, practical measurements, and observations). Included also in this category are the dependence on frequency and phase errors—discussed in detail previously—which appear in tracing h.f. phenomena when the time occupied by the electron in crossing the field is comparable with the duration of the event to be recorded (see pp. 92–97). A considerable effect on precision of measurement is exercised by internal charges (on the glass walls) which were eliminated for the first time by tubes metallized internally or externally.

In order to avoid disturbances caused by uncertain charges on the deflection plates, those plates which are not in use should be connected to the anode directly, or, in cases where this is not possible, through resistances of the order of 10^6 ohms.

Naturally, of course, care should be taken that errors in measurement do not occur through the influence of stray external fields on the cathode-ray tube. Information has been given in another part of this book about the control of stray fields. Other errors in precision measurements occur through purely geometrical conditions. In this connexion the oscillogram is more accurate the smaller the ratio of spot diameter to the diameter of the workable portion of the screen, i.e. the greater the resolving power. The diffusion of the spot in tracing high frequencies results in a very large decrease in the resolving power of the gas-filled type of tube. The use of screen contact photography also causes accurate measurements to be affected by the spreading of the spot which is very difficult to avoid. An error which is due to the geometry of the tube but one which can be ignored frequently, results from the essential curvature of the bowl of the tube, a shape which is adopted for constructional reasons. This error is naturally smaller the less the ratio of maximum amplitude to screen diameter, since the curvature is least at the centre of the screen. The

error in deflection where external observation is concerned is

$$\Delta y = y^3/2RL_2 \quad . \quad . \quad . \quad . \quad (42)$$

where L_2 is the distance from the centre of the deflection plates to the fluorescent screen, y the deflection, and R the radius of curvature of the screen.

For accurate reproduction of high definition television pictures, which has been made possible with the modern high-vacuum tube, measurements with accuracies which a few years ago appeared impossible are necessary, and such tubes are more accurate than many instruments for measuring small currents.

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CHAPTER II

ACCESSORIES

BOTH for general use and for particular applications, the cathode-ray tube requires auxiliary apparatus the design of which must, in order to secure efficiency of the whole equipment, be of as great importance as the tube itself. Quite apart from the object of any particular application, a complete set of equipment supplying the various voltages required by the tube, is always needed.

I. SOURCES OF ELECTRIC SUPPLY FOR CATHODE-RAY TUBES

The supply for the cathode-ray tube must provide potential for one or more anodes, for the focusing electrode and the heater circuit. The provision of the anode voltage usually entails the highest power consumption. Besides the provision of high voltages, a step-by-step or uniform regulation of the accelerating voltages within wide limits is, in many cases, desirable. As the performance of the various types of modern tubes does not vary very much, the brightness of the spot attainable is to a great extent dependent on the value of the anode voltage. The curves for a high-vacuum tube, shown in Fig. 165, afford some idea of the way in which the brightness of the fluorescent spot depends on the magnitude of the anode voltage. The brightness of the spot depends much more on the anode voltage in the lower range than in the upper range as a result of the difference in screen efficiency. The measurements of Fig. 165 show this. In the case of ray currents usual in modern cathode-ray tubes, the following conditions of operation exist in the respective voltage ranges.

With anode voltages of 200–400 volts, the brilliancy of standing figures is sufficient for observation in undarkened rooms provided short gas-filled tubes with relatively small screens are used. Large tubes designed for operation at higher anode voltages produce fluorescent patterns which can be satisfactorily viewed in dark enclosures. Observation of non-recurrent phenomena can hardly be considered with low anode

voltages, since the illumination is too low. In the 400–800 volt range the maximum tracing speed is sufficient to enable visual observation of low-frequency non-recurrent events to be made in darkened enclosures. Even with voltages of this order, though preferably in the 800–1 200 volt range, the brightness of the spot is sufficient to enable the tube to be used for measurement and control of working operations. Within the whole anode voltage range, from the lowest potential at which fluorescence appears, photographs of stationary patterns can be taken satisfactorily. Photographic recording of low-frequency non-recurrent figures requires voltages over 1 200. Almost all high-vacuum tubes need anode voltages over 2 000 to obtain a brilliant spot. Voltages between 1 000 and 2 000 are necessary to record components in the oscillogram which lie near the upper limit of the low-frequency range, with a screen amplitude of several centimetres. Voltages of this order are used in tubes for sound-film recording and for television, where the energy of the fluorescent spot is spread over a large surface. Anode voltages exceeding 4 000 volts are used only in high-vacuum tubes for investigations involving small currents. In most gas-filled tubes the focusing effect ceases near this voltage and there is a tendency for a discharge to pass. With voltages of 4 000, it is possible to obtain tracing speeds which enable photographic recording of medium frequency phenomena, with amplitudes of several centimetres, to be made.

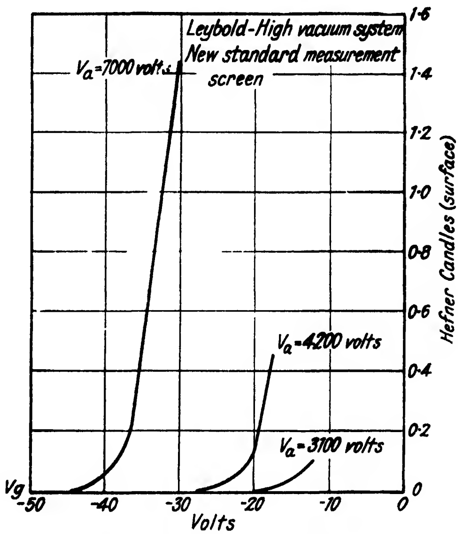


FIG. 165. ANODE VOLTAGE AND LIGHT INTENSITY CHARACTERISTIC FOR A HIGH-VACUUM TUBE

1. **Battery Operation.** In all cases where supply mains are not available or where connexion to them is undesirable,

potentials for operating the tube must be supplied from batteries. Such supply is of importance for portable equipment. As the anode and heating circuits seldom consume as much as 2 watts, operation from batteries is economical in spite of the fact that the provision of the anode voltage of 1 000 volts from dry cells is a disadvantage. Alternatively, attention can be given to d.c. converters which will be discussed in greater detail later.

The anode current of the present-day tubes in practice is about 0·02 to 0·4 mA. The ion current, which in gas-filled tubes flows to the negative focusing electrode, is about one-hundredth of this. The current flowing to the negatively biased brightness control grid can always be ignored in high-vacuum tubes. As fluctuations of 10 volts in the anode voltage hardly affect the properties of the tube to any extent, and this corresponds to a resistance of 10^5 ohms in the electron current circuit, it is of no disadvantage to have a resistance of this order in the anode circuit. Although much smaller voltage fluctuation on the control electrode is permissible, the current in this circuit is also much smaller, so that the internal resistance should be about 5.10^5 ohms, in order that critical back coupling may not arise. The internal resistance of the supply for one or more of the lens electrodes may, as a rule, be of the order of a megohm. The current in this case is generally so low that no material change in voltage occurs with the resistance of the order stated, even when the system includes apertures, when adjustment of the brightness control grid is correct and suitable choice of accelerating voltage is made. In order to minimize changes of voltage in the lens electrodes due to the accumulation of charges for short periods from the apertures during over-modulation periods, as for instance in television reception, a capacitance can be arranged to neutralize such peaks. The possibility of having such high internal resistances in the anode and cylinder circuits is of great advantage, since the source of potential becomes less dangerous to the operator with these resistances in circuit. If portions of the circuit at high voltage come in contact with one another, the potential difference immediately falls to zero. Furthermore, a high internal resistance in the anode and cylinder circuits has the advantage in gas-filled tubes that it prevents the passage of a discharge which would otherwise destroy the electrode system. The possibility of a very high ion current of a magnitude

dangerous to the tube is also avoided owing to the great drop in voltage which would take place. The prevention of the gas discharge is of great importance when working with anode voltages of several thousand. In addition, there is the advantage that the voltage dividers necessary for modern arrangements may be of very high resistance, and therefore consume very little power from the source of supply. Most voltage supplies, especially batteries, have internal resistances very much less than 10^5 ohms, so that in such cases a resistance of this order must be included in the circuit. The ordinary high resistances are suitable if their value is independent

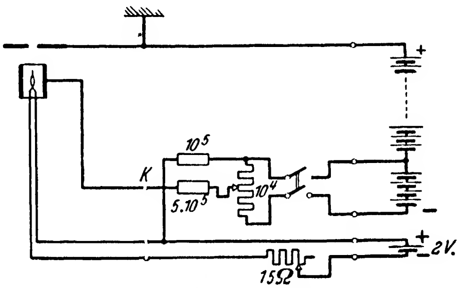


FIG. 166. CIRCUIT FOR BATTERY OPERATION (200-500 V.)

of the load. Precaution should be taken against using the so-called *vacuum resistances*, most of which are not enclosed in a high vacuum and which, on the occurrence of a short-circuit, allow the current to bridge the resistance path by a glow discharge.

A suitable circuit containing protective resistances for battery operation is shown in Fig. 166, and is one using an old type gas-filled tube. In place of two protective resistances it is sufficient to connect one across the leads to the anode. The arrangement is one which is also fairly general for low voltages. In the case of very high voltages it is inferior to the circuit of Fig. 166, since as long as only the anode is protected, a gas discharge may still take place between the deflection electrodes on the one hand, and the cathode or cylinder on the other. If the deflection plates are also protected by a series resistance, a disturbance of the position of the ray may easily occur as a result of the drop in voltage across the resistance. The method of connecting up the protective resistances according to Fig. 166 is therefore strongly recommended. Fitting the

protective resistances near the tube has the advantage of keeping the conducting parts, especially the leads to the focusing electrode, as short as possible, so that stray capacitances from external sources, such as near-by mains, etc., do not induce voltages of appreciable magnitude. In order to maintain the source of current at some definite potential, it should be earthed. Earthing the cathode as in the case of amplifiers has the advantage that accumulators which may be used for heating, will be at earth potential, but this arrangement is only suitable for tubes operated without electrostatic deflection for measuring purposes. When electrostatic deflection is used, the anode is almost invariably earthed as in Fig. 166. In this way the deflection plates and, also, the associated circuits used with them, can be kept at earth potential. In order to operate an old type of tube by means of the circuit of Fig. 166, the cathode should be raised, gradually at first, to the required temperature, including, if necessary, an ammeter in the heating circuit. A special switch has not been placed in the heating circuit. This has been omitted intentionally so that one is compelled to turn back the heating rheostat when switching off, so that overheating previously mentioned does not occur when the circuit is re-established, an occurrence which might otherwise take place when the partly-discharged accumulators have recovered. Anode and potentiometer voltage should only be switched on together after the heating has been adjusted. By the aid of the potentiometer connected to a portion of the battery, it is easy to find the most satisfactory voltage for the focusing electrode, consistent with maximum brightness of the spot and optimum focus of the rays.

Regulation of the cylinder voltage should be possible in all equipment where extreme sharpness of the spot is required, and where limitation of the number of controls is not important. It is desirable to limit the range of adjustment for the voltage of the focusing electrode by including a fixed resistance in series with the potentiometer or some other contrivance which prevents overloading the cathode, such conditions arising where the cylinder is at zero or at a low negative potential. The optimum negative bias of the focusing electrode is in gas-filled tubes according to the value of the anode penetrance existing at the time, about one-tenth to one-fifth the magnitude of the anode voltage.

In order to obtain control by the Wehnelt cylinder in Fig. 166,

it is only necessary to lead the a.c. control voltage through a capacitance to the terminal K. As the source of the a.c. control voltage will generally have one pole earthed, this capacitance must be able to withstand a test voltage which will ensure its satisfactory performance when subjected to the full accelerating voltage of the tube. The capacitance must be of such a value that the voltage drop across it at the given frequency is small compared with the drop across the $5 \cdot 10^5$ ohm resistance in the cylinder circuit. Very high capacitances ($> 1\ \mu$F.) should not be used at this point, particularly with high anode voltages,

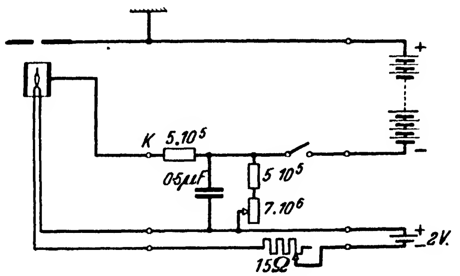


FIG. 167. SIMPLIFIED CIRCUIT FOR AN OLD GAS-FILLED TYPE TUBE IN WHICH THE CYLINDER VOLTAGE DEPENDS ON THE ANODE CURRENT

since their capacitance currents alone can lead to the production of a high gas discharge which may result in the destruction of the tube.

In consequence of the ease of adjustment of all the voltages, the circuit of Fig. 166, or one with voltage divider for feeding one or more lens electrodes, is suitable for tracing the anode current/cylinder voltage characteristic of the tube as well as, in fact, for making measurements with the tube. Another simplified circuit in which the bias of the focusing electrode is taken through a separate resistance, since voltage drop is caused by the anode current itself, is shown in Fig. 167. The dependence of the cylinder voltage on the existing anode current is an advantage, since the increase in anode current is arrested by the automatic increase in the bias which it produces. This arrangement of connexions is specially recommended where sudden alterations in anode voltage may occur (as, for instance, when connected to lighting mains). The accelerating voltage between anode and cathode which determines the ultimate electron velocity, and therefore the sensitivity of the ray,

naturally varies according to the cylinder voltage. In tubes having a very steep anode current/cylinder voltage characteristic the change in cylinder voltage necessary for light-dark control hardly amounts to more than 10–20 volts. The change in velocity due to regulation of the cylinder voltage in this circuit is so small that the sensitivity of the tube can be regarded as being independent of the cylinder voltage adjustment. In the circuit of Fig. 167, a fixed resistance is connected in series with the variable non-inductive high resistance to

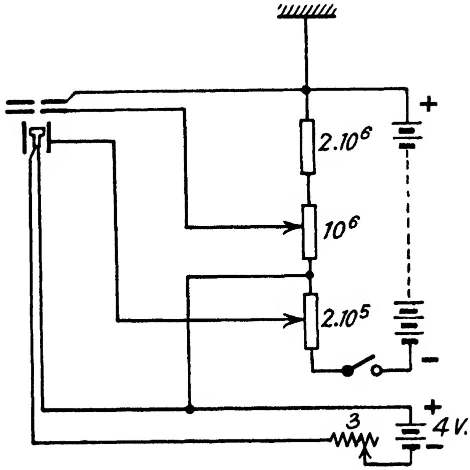


FIG. 168. CIRCUIT FOR MODERN BATTERY-OPERATED TUBES WITH ACCELERATING LENS

limit the regulation of the cylinder voltage. This limitation is advisable particularly in view of the use of the tube for calibration.

The by-pass condenser included in almost all the mains circuits, mentioned below, is scarcely necessary for battery operation. It is, however, included to prevent back coupling between anode and cylinder voltage, which results in a flattening out of the control characteristic when brightness control is carried out by means of a Wehnelt cylinder. The values in Fig. 167 are so arranged that the steepness of the control characteristic appreciably decreases at a.c. control voltages of frequencies less than about 25 cyc. Fig. 168 shows a circuit with a voltage divider for battery operation of modern tubes with an accelerating lens. Additional safety resistances

are not included in this circuit, since the high-vacuum tube and those with low gas pressure are free from the danger of gas discharge. If the tube used has an indirectly heated cathode, care should be taken that the time required for the heat temperature to reach its maximum, which is from 1 to 2 min. according to the design, elapses before voltage adjustment is made to secure optimum brilliancy and sharpness of the spot. Operation by dry cells is inconvenient when voltages of several thousand are necessary. In such cases it is preferable to convert high current at low voltages, such as are obtainable from accumulators or dry batteries, to high voltage low current supplies by suitable converters. To obtain high voltage d.c.

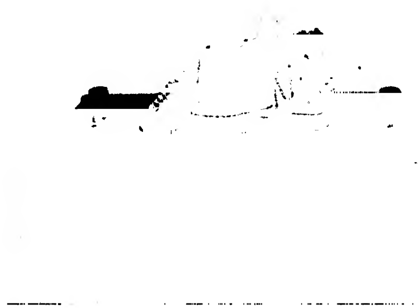


FIG. 169. PENDULUM CONVERTER (FALKENTHAL) FOR OBTAINING ALTERNATING CURRENT FROM ACCUMULATORS

it is first necessary to convert d.c. to a.c. A number of ways in which this can be done will be discussed in turn. A simple method of obtaining a.c. from a d.c. source is by means of a Falkenthal's pendulum converter. Such a converter, shown in Fig. 169, supplies a fairly constant a.c. of about 500 cyc. if the make-and-break contacts are properly adjusted. This current is useful for producing high direct voltages with mains equipment and rectifiers. An example is shown in Fig. 170. The cathode of the rectifying valve is connected to a low voltage winding on the secondary side of the transformer. The a.c. output is sufficiently constant for heating the filament of the rectifier, but not for heating the cathode of the tube by an additional winding. In order to correct irregularities in the alternating voltage supplied by the converter, a smoothing circuit with very low-frequency cut-off must be provided. This requirement is easily satisfied for small currents, and can be

dealt with by the simple resistance-condenser circuit of Fig. 170, in which oscillations of period greater than 20 sec. are eliminated. Usually, much shorter tracing periods than this are involved for purposes of measurement and for tracing oscillograms, so that this smoothing is quite sufficient. The equipment in Fig. 170 simply replaces the anode battery in Fig. 167. By adjusting the variable resistance shown, the voltage supplied to the equipment can be altered within limits. High-frequency circuits are particularly suitable for the production of high voltages from batteries; these will be described in the next section. The equipment indicated below with which the

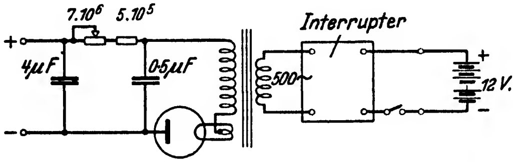


FIG. 170. EQUIPMENT USING THE PENDULUM CONVERTER FOR PRODUCING HIGH VOLTAGE D.C.

direct current is converted, by means of "saw-tooth" oscillations, into a.c. suitable for transformation, is also used in connexion with batteries.

2. **Equipment for D.C. Mains.** In the circuit of Fig. 167, d.c. mains can be used instead of batteries. Earthing can then simply be omitted, or it can be ascertained whether one pole of the d.c. supply is permanently earthed. Generally, the a.c. superimposed on the d.c. is so small in amplitude (1–2 per cent of the d.c. voltage) that no smoothing circuits are necessary.

Of course, operation from lighting mains involves the mean value of the voltage fluctuating according to the time of day and the consumers' load. In some cases these variations amount to 10 per cent or more. It is advisable, therefore, especially in the case of the older gas-filled tubes for mains operation, to make the cylinder voltage dependent on the anode voltage. Sudden voltage surges, which as a result of the change in sensitivity they produce alter the tracing of oscillograms, are smoothed out in most of the mains operated circuits given below. If neon stabilizers or other regulators are not provided for smoothing out the mains voltage, it is necessary to calibrate the sensitivity of the tube by a voltage of known value or by a known magnetic field. This should always be done before

using the tube when precision measurements are to be made. In principle, it should be noted when using d.c. from mains supply, that at 220 volts the operation of the tube is severely limited on account of the tracing speeds which are attainable at this voltage. For the same reason, 110 volts is not sufficient unless conversion to a higher voltage is to be made. This conversion can be made by a motor generator, and has the advantage that the anode voltage of the tube can always be regulated within wide limits by altering the field excitation of the high voltage generator. The high cost and the inconvenience of servicing the high-voltage generator are its disadvantages. The use of high-voltage machines is hardly practicable even when such equipment is available for other purposes. Another method consists in converting the d.c. to a.c. by means of rotary or static inverters, the high-voltage supply units being connected to the a.c. side. This will be discussed in more detail in the following section. Such a method has the advantage that the heating current is also supplied from the lighting mains corresponding to the a.c. circuit given later on in the book.

Static inverters are the recently produced so-called *a.c. converters*, which, by means of thyratrons, produce a sinusoidal a.c. supply of 50 cyc. of remarkable constancy. Fig. 171 shows the circuit of a self-excited push-pull inverter(1) which represents the converse of the single-phase full-wave rectifier. Two thyratrons operate in push-pull in such a way that current flows alternately through the upper half and then the lower half of the transformer winding. The grids at the same time can be controlled by a special timing impulse.

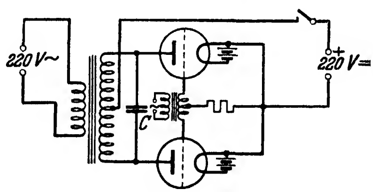


FIG. 171. SELF-EXCITED PUSH-PULL A.C. INVERTER

However, self-excitation is generally used, i.e. the primary winding of the grid transformer will be connected to the a.c. output. Frequency adjustment is made by means of phase displacement in the grid transformer. The equipment is then self-regulating. Commutation is facilitated by the condenser *C* which, during the period of de-ionization, removes the anode voltage from the tube whose discharge is extinguished.

Components should be chosen so that a frequency of about 50 cyc. is obtained. Another method of using the alternating inverter consists of the series circuit shown in Fig. 172. Two condensers acting as sinks of energy are alternately charged and discharged through grid-controlled rectifiers. The condenser

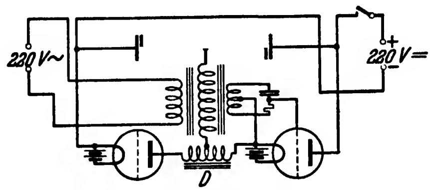


FIG. 172. SERIES ALTERNATING CURRENT INVERTER

current is alternating, and is either taken direct or, in the case under review, through a transformer. A choke *D* included in the circuit facilitates commutation. The arrangement here is self-adjusting. Another transformer circuit without mechanical moving parts is shown in Fig. 173. Here a high-frequency

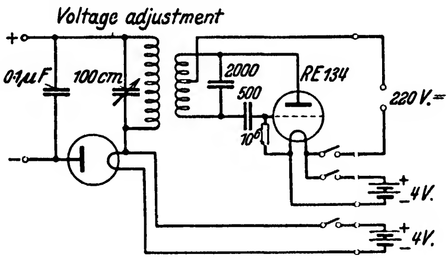


FIG. 173. H.F. EQUIPMENT FOR PRODUCING HIGH VOLTAGE D.C.

ocillator of the usual type is operated from d.c. mains, and its oscillating circuit is coupled to a Tesla coil. The high-frequency voltage in the Tesla coil can be simply adjusted by a variable condenser of low maximum capacitance connected in parallel on the secondary side. Rectification takes place with an ordinary rectifier valve which is heated by an insulated accumulator separate from the rest of the circuit, and not from the h.f. supply. There are two ways of smoothing out the a.c. components in the lighting mains. The smoothing may precede the anode circuit of the oscillator or the smoothing here may be omitted; in the latter case, the oscillator produces modulated high-frequency current which must

be smoothed by a large capacitance (0·1 μF.) following the rectifier valve. The latter is the more convenient method, although it lacks the advantage of the first, that danger from contact cannot occur on the d.c. high voltage side, since the output at the moment of contact is low on account of small capacitance of the circuit. As distinct from all other mains circuits discussed below, the high-frequency transformers permit of contact being made with the unrectified high voltage without danger. High-frequency apparatus has not been extensively used on account of the rather complicated circuits involved and the danger of radiation, which can only be prevented by careful screening of all components.

Most of the circuits so far described for taking high anode voltage from d.c. mains have an alternating voltage component in their supply. Feeding anode supply from a.c. lighting mains, therefore, does not involve any differences in principle. The construction of a.c. mains equipment is, in fact, simpler. Suitable a.c. converters have recently been manufactured on a larger scale following the principle of the pendulum converter mentioned above. Vibrators working at a frequency of about 100 cycles are used, and are driven from batteries or d.c. mains. They give satisfactory performance over long periods. When feeding high tension units for cathode ray tubes, no limit is set by the maximum load, so that the tube may be heated from a special winding on the transformer.

Considering the remarkable progress made with this type of converter the aforementioned equipments using thyratrons, etc., may easily be dispensed with.

Finally, an entirely different method of converting direct voltage, for use with cathode-ray tubes, should be mentioned here. As distinct from the circuits previously described there is no a.c. component in the supply. The conversion is carried out by charging a limited number of condensers connected in parallel from the d.c. source, and then changing their arrangement to series connection before discharging, the switching being carried out by a vibrating or rotary device. Naturally the h.t. voltage is proportional to the number of condensers and the output is sufficient for all normal requirements. Converters of this type are widely used in industry, e.g. for testing condensers.

3. A.C. Mains Equipment. As far as the production of voltages up to 500 are concerned, the usual mains equipment

used for radio is satisfactory. As the current consumption is small, half-wave rectification is sufficient. Altering the usual mains equipment from full-wave to half-wave rectification, using the same components, enables the voltage to be doubled. Care must be taken that the smoothing condensers are equal to withstanding the higher voltage without risk of breakdown. If necessary, the parallel connexion of the condensers can be altered to series connexion with corresponding alterations to the voltage divider. A simple a.c. mains circuit in which ordinary radio components are used is shown in Fig. 174. Heating is carried out by means of an accumulator. If the tube used has an a.c. cathode, heating can be taken from a winding on the transformer. The circuit of Fig. 174 complies with the requirements detailed above. A practical example of apparatus using the circuit of Fig. 174 is shown in Fig. 175. The various controls are easily accessible. The tube holder is fixed on the case. The transformer in the equipment is prevented from causing disturbance of the ray through its stray field by suitable orientation.

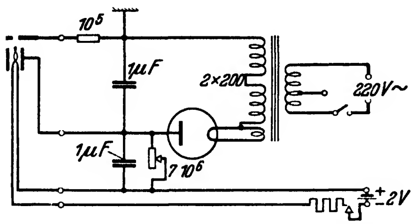


FIG. 174 CIRCUIT FOR ANODE VOLTAGE FED FROM A.C. 220–500 V.

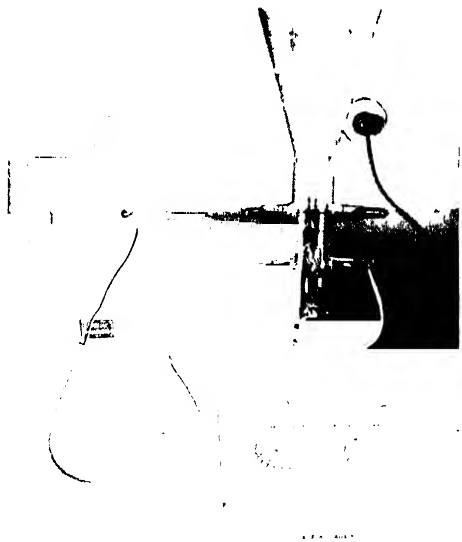


FIG. 175. A.C. ANODE CIRCUIT EQUIPMENT WITH TUBE MOUNTING

Fig. 176 shows the circuit of an a.c. mains equipment which provides all voltages, including the heating supply for an older type of gas-filled tube. Various tappings from the high voltage winding of the mains transformer can be selected by a multi-contact switch. A protective resistance of $5 \cdot 10^5$ ohms has been included at the highest voltages, and this should be short-circuited only in cases where the highest tracing velocity is demanded from the tube. The voltage of the cathode winding should advisedly be chosen only slightly higher than the highest permissible voltage for the cathode. By this method of design, a burn-out of the cathode through incorrect adjustment over a short period is avoided. The entire smoothing is provided by the two condensers. Special protective resistances are not necessary for this circuit as long as the smoothing condensers have the stated values. The only condition is that the transformer and rectifier valve furnish

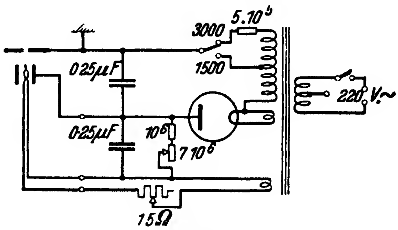


Fig. 176. A.C. Mains Unit for All Voltages

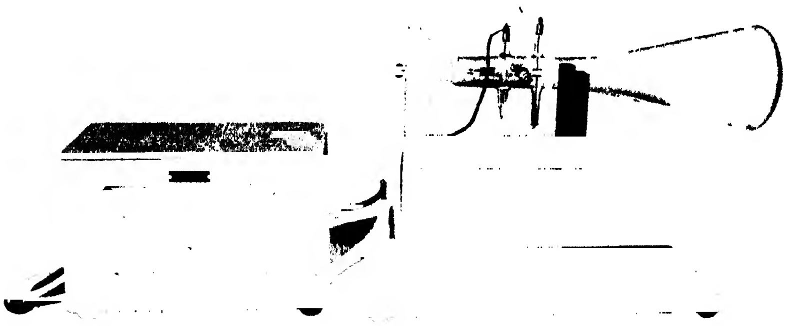


Fig. 177. A.C. Mains Unit for 1 500–3 000 v. Anode Potential Heating and Cylinder Voltage Continuously Adjustable (*Leybold N.A.G.*)

currents which are only of a few milliamperes. Valves with pure tungsten filaments, and formerly used for amplification, are suitable for rectifying high voltages. The tungsten cathode

with its low emission necessitates the current being limited to a low value, and at the same time requires an increase in the charging time which is of the order of 0·5 sec.

Fig. 177 shows a mains equipment which has become quite general in practice and whose circuit agrees closely with that of Fig. 176.

High-vacuum tubes, as has been pointed out repeatedly, require anode volts of 3 000 or 4 000 for operation. Anode voltages up to 6 000 are used to obtain particularly high tracing speeds or brilliant television pictures. Furthermore, in the

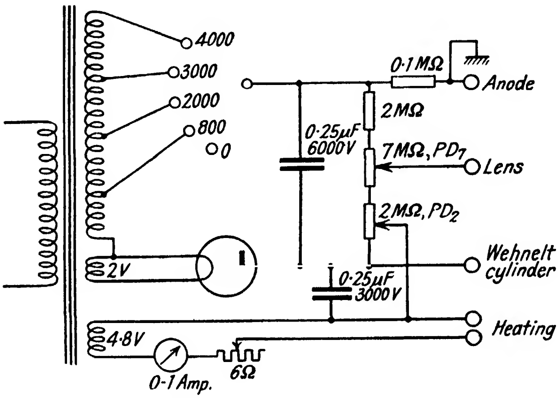


FIG. 178. MAINS EQUIPMENT FOR HIGH-VACUUM AND GAS ELECTRON-RAY TUBES WITH ACCELERATING LENSES

operation of these tubes, a positive voltage is necessary for the lens electrode which must be adjustable with accuracy to get the optimum sharpness of the spot. The range of adjustment should be variable between 0·2 and 0·3 of the anode voltage.

Constant voltage regulation is also necessary for the negative bias of the brightness control electrode. This part of the supply should be capable of giving an adjustable range of — 100 volts to — 150 volts. Furthermore, a source of heating current capable of supplying 0·5 to 0·6 amperes at a maximum voltage of 4 is necessary. If the voltage has not at first been adjusted to the rating of the cathode-ray tube, it is desirable to set it at about 4·8 volts and adjust the current to its rated value with a variable resistance and ammeter. A simple circuit for the operation of modern tubes with accelerating lenses is shown in Fig. 178. With the relatively low current rating of modern

indirectly heated cathodes, and the effective screening of their magnetic fields, disturbance of the position of the spot they cause can be disregarded. In indirectly heated cathodes,

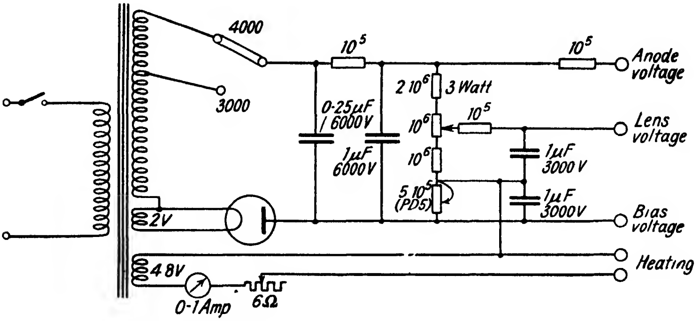


FIG. 179. MAINS UNIT IN WHICH THERE IS AMPLE SMOOTHING FOR TELEVISION PURPOSES

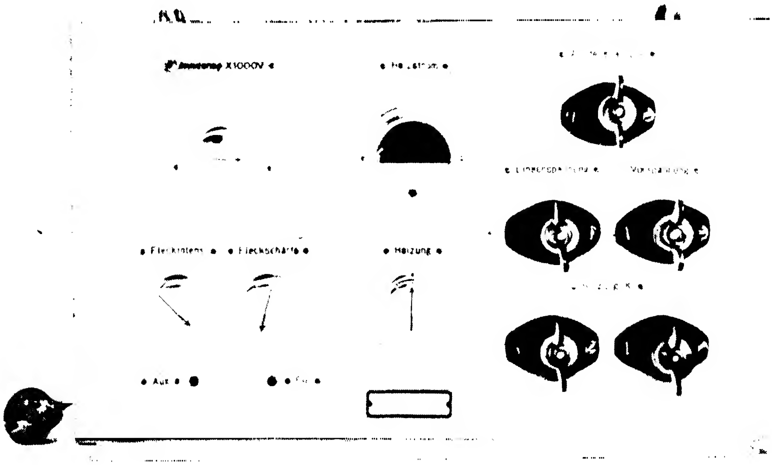


FIG. 180. MAINS-OPERATED EQUIPMENT (UNIVERSAL TYPE) FOR ANODE VOLTAGES UP TO 4 000 V. (*Leybold and von Ardenne*)

however, care must be taken that the heater terminal in Fig. 178 is connected to the pin of the tube base which leads directly to the equipotential surface. Another circuit for television purposes, in which smoothing is carried still further, is shown in Fig. 179. External and interior views of the equipment using the circuits of Figs. 178 and 179 are shown

respectively in Figs. 180 and 181. Special valves are essential for the rectification of high voltages, and the anode and cathode must be taken out at different points on the bulb. In addition,

FIG. 181. INTERIOR VIEW OF THE A.C. MAINS EQUIPMENT OF FIG 179

the rectifier must have a relatively large anode spacing and stable cathode to prevent the latter being destroyed by strong electrostatic attraction. As the ray stream when the tube is in operation is small compared with the current of about 1 mA. in the voltage divider shown in the diagram, it is sufficient to design the transformer, rectifier and smoothing circuit so that the current in the circuit is rather more than 1 mA. It is not advisable to increase the output of the rectifier

and the degree of smoothing much more than that shown in Fig. 179, as otherwise danger from high voltages would be increased unnecessarily. For instance, the resistance in the lead to the anode terminal has again been inserted simply to limit the current in the event of the parts carrying high voltage being touched accidentally by the operator. Complete mains operation which renders the tube ready for immediate use by the action of a single switch enables the apparatus to be available in a form which satisfies all the requirements of a measuring equipment.

II. Increasing Sensitivity by Amplification

The sensitivity of cathode-ray tubes varies between 2·0 and 0·1 mm./volt according to the anode voltage and size of plate employed. In order to obtain fluorescent figures with sensitivities of this order, which will attain a size of 10 cm., i.e. which will load the fluorescent screen fairly well, fluctuations in the instantaneous value of the incoming voltages over a range of 50–1 000 volts are necessary. If sinusoidal voltages are involved and are to effect the loading mentioned, about 200 volts r.m.s. are necessary for tubes with a sensitivity of 0·2 mm./volt, and for tubes with a sensitivity of 2 mm./volt, 20 volts r.m.s. are necessary for deflection over the screen range mentioned. Voltages of such magnitudes are not always available, and in such cases it is necessary either to be satisfied with smaller patterns, which result ultimately in too low an accuracy in measuring, or to use amplifiers which will increase the voltage to be examined to an extent that voltages of the order given above can be made available.

Amplifiers for increasing the sensitivity of the cathode-ray equipment must have not only the necessary degree of amplification which is the quotient of the input voltage to the tube and voltage being measured, but they must not introduce any distortion in the voltage characteristic under examination. The demands made on the equipment in this connexion are considerably greater than are required for ordinary high frequency and acoustic amplification. Distortion of voltage characteristic may occur as a result of the fact that amplification is not linear with amplitude or frequency. To avoid this, amplification must be the same for all frequencies which are present in the signals to be measured. If components below

25 cyc. are present, and particularly if very slow variations to the steady values are also to be amplified at the same time, recourse must be had to direct coupled amplifiers. If frequency components lower than 1 cyc. are absent, then special amplifying circuits with stabilized stages may be employed, thus avoiding the disadvantages of direct-coupled circuits.

If frequencies below 25 cyc. are not present, the usual a.c. amplifying circuits can be employed. The design of the amplifier becomes more difficult the greater the frequency band to be considered. Constant degree of amplification over a wide frequency range can be attained by using correctly designed resistance coupling. The performance of the amplifier in respect of signal amplitude depends on the linearity of the last stage, since by far the highest alternating control voltages are present at this point. The last valve in the amplifier must be capable of supplying undistorted sinusoidal voltages of 20–400 volts r.m.s. according to the sensitivity of the tube. This requirement is unusual and not easy to fulfil. For this reason, the components of the last stage will next be considered in detail. The first step in designing a stage of amplification is to consider the characteristics of the circuit to which the valve is to be connected. In the case under consideration, the plate resistance of the tube is to be matched. It was stated in greater detail above that the plate characteristic required a coupling resistance not greater than 10^5 ohms for gas-filled tubes, or 10^6 for modern tubes. It is desirable in order to secure independence of frequency for the coupling to be a non-inductive resistance. Further, in such cases where no doubt exists about the frequency dependence, the tube should not be coupled through a choke or transformer, since distortion of the curves may easily occur with the large amplitudes present at this stage, and they are difficult to control. The last stage of the amplifier should be so designed, therefore, that it provides as high an alternating voltage in an undistorted form as possible across a resistance of 10^5 or 10^6 ohms. In good modern valves it is possible to get characteristics in combination with anode resistances of the order of 10^5 ohms which result in linear operation over a wide range.(2) The anode resistance is large compared with the internal resistance over wide limits of the characteristics in modern tubes. The result is that the characteristic is almost perfectly straight over a considerable portion of its path. The working characteristics of an example of a

normal triode (amplification factor 10) with an anode resistance of 10^5 ohms are given in Fig. 182 with various anode voltages. The characteristics follow practically the same outline for other battery or mains valves with the same amplification. The range of perfect linearity in the characteristics has been indicated clearly in Fig. 182, and the most satisfactory point for operation is shown in the centre of this range. On another ordinate scale, the voltage drop across the anode resistance at the various anode current values of Fig. 182 is shown. It is possible, therefore, to read straight off from this

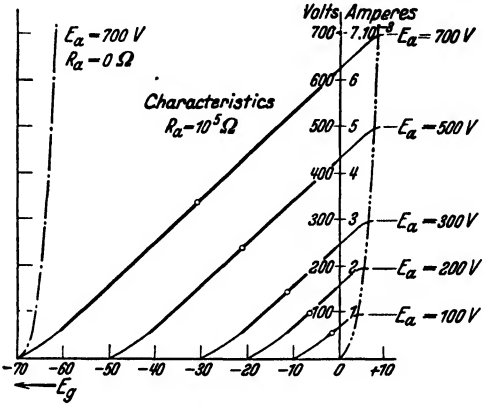


FIG. 182. OPERATING CHARACTERISTICS OF THE REN 1104 VALVE WITH AN ANODE RESISTANCE OF 10^5 OHMS AND VARIED ANODE VOLTAGE

diagram the voltage range over which the valve has a linear characteristic when used with a resistance of 10^5 ohms. The lower limit set by the bend in the characteristic and the upper limit of the modulation range imposed by the existence of positive grid current, means that with an anode voltage of 700 the undistorted voltage range available is about 560. At this high anode voltage the most favourable conditions are obtained, i.e. about 80 per cent of the voltage of the supply is available. This proportion decreases very quickly as the anode voltage drops. At 500 volts the undistorted voltage available is 370, at 300 volts about 190, at 200 volts about 100, and finally at 100 volts only about 10. From the examples given the anode voltage which must be available at the last stage of the amplifier to meet the sensitivity requirements of

the cathode-ray tube can be obtained by interpolation. For instance, in order to obtain an undistorted fluorescent figure of 10 cm. diameter with a tube of 0·2 mm./volt sensitivity, the anode voltage of the last stage must be at least 650, with a sensitivity of 0·5 mm./volt at least, 310 volts, with a sensitivity of 1·0 mm./volt. at least, 200 volts and 150 volts with a sensitivity of 2·0 mm./volt. If a push-pull output stage is used (see below), the undistorted voltage available is nearly doubled. A circuit of this kind is therefore recommended also if symmetrical output voltages are not necessary or desirable for other reasons. The anode voltages which are very high indeed are not detrimental to ordinary amplifying valves, since the anode losses are low. At the most they amount to 2–3 watts. About the same power is converted into heat in the anode resistance so that a high load resistance must be used. The diagrams and examples given will be sufficient for the correct design of the output stage of the preliminary amplifier. In the linear portion of the characteristic the amplification is almost always equal to m, where m = amplification factor ($1/D$). The voltage range in the penultimate stage controlling the output stage is smaller corresponding to the actual amplification. When the penultimate stage is operated from the same high anode voltage as the last valve, the voltage range is always much greater than is essential for undistorted amplification. This also happens when a valve of higher amplification factor is used to obtain greater gain in the output stage. In equipment where complete independence of frequency is demanded, it is desirable to use valves of the highest slope in the first stages. In amplifiers for increasing the sensitivity of cathode-ray equipment, the same type of valve with the same design is often used in all stages. In equipments with a high degree of amplification only the last stages differ from the first by the use of higher voltages and possibly mains operation.

1. **Pre-amplifiers for A.C. Voltages.** The design of circuits for a.c. voltage amplifiers has been so thoroughly treated in the various textbooks[3] available that it would be superfluous to cover the ground again here. The special points of construction of valve amplifiers for measuring purposes suitable for calibration have been made the subject of special treatment on many occasions,[4] and the methods of testing and calibrating them have also been discussed in detail elsewhere.[5]

Amplifiers for increasing the sensitivity of cathode-ray tube

equipment as outlined in greater detail above, are conveniently constructed with resistance coupling and all stages designed alike. One method of calculation(6) for resistance amplifiers with similarly designed stages, which is readily understood, consists of regarding the amplifier as a heavily damped oscillatory circuit. Resistance amplifiers, which are free from frequency distortion over the range 100 to 8 000 cyc., are widely used for radio and sound-film work. By making the coupling condensers between the valves larger, a limit to which is set by relaxation oscillations, the lower limit of frequency response can be extended to about 20 cyc., depending on the internal resistance of the current supply. In fact, by inserting symmetrical stages, the lower limit can be brought down to less than 1 cyc. without making the amplifier unstable. By using valves of low capacitance and impedance and by employing small coupling resistances, the upper frequency limit can be raised considerably. Resistance coupled amplifiers can be constructed with ordinary components which will give distortionless amplification of considerable magnitude over the range 25–100 000 cyc. The use of multi-electrode valves enables amplifiers which have no appreciable falling off in frequency response below 10^6 cyc., to be constructed. The possibilities of so increasing the upper frequency limit have already been treated in detail.(7) The characteristics which permit still further increase in the frequency limit to 10^7 cyc. and the amplification of limited frequency bands in the region $4 \cdot 10^7$ cyc. are also given in another paper.(8) During the development of amplifiers for television transmission circuits, designs have been evolved which enable, even with ordinary commercial valves, frequency characteristics to be obtained which show a constant degree of amplification from very low frequencies up to 10^6 cyc.

In this connexion reference may be made to an American publication.(9) With the aid of the references quoted, it should certainly be possible to fix the design and circuits of amplifiers which must have special characteristics for particular problems. For most problems occurring in practice, the amplifiers and the design discussed below in this section will be sufficient. Distortion in the characteristic form of curve which occurs when the voltage to be measured has components which are near or outside the frequency range of the amplifier is difficult to deal with. Phase displacements which occur near the frequency limits of the amplifier cause considerable variation in the outline of

the curve. Obviously, therefore, the amplifier should not be used near its frequency limits. Distortion caused by the upper and lower limits of frequency response in a resistance-coupled amplifier has already been investigated elsewhere for a particularly simple characteristic curve.[10]

In some cases, only narrow frequency bands have to be amplified. In this connexion reference may be made to the investigation of modulated high-frequency oscillation. Tuned oscillatory circuits can be used for the amplification of narrow frequency bands, not only for coupling the valves, but also the cathode-ray tube. It is merely necessary to ensure—perhaps by artificial damping in the circuit—that the resultant tuning band is at least two or three times the width of the frequency band under observation. If this condition is fulfilled, critical alteration of the shape of the curve due to frequency distortion and phase displacement need not be anticipated. As tuned amplifiers are only infrequently necessary, mostly for high-frequency technique, and as their design is familiar to every technician, it is not necessary to go further into details here. It is possible, whether tuned or aperiodic amplifiers are used, that unavoidable changes in the degree of amplification and distortion of the curve will result from a tendency to oscillate.

The greater the amplification in the preliminary amplifier, the greater the back-coupling factor and the greater the possibility of disturbances through tendency to oscillate. In the usual circuits for measuring with the cathode-ray tube, the deflection plates connected with its lead-in wires to the output of the amplifier are not generally screened, and in addition, for convenience, the measuring circuit connected to the amplifier input is also unscreened. The back-coupling factor in such cases often reaches a value of 10^{-3} or 10^{-4}, especially when there is a high input resistance in the amplifier, so that amplifications of 10^3 or 10^4 are quite sufficient, with suitable phase relationship, to give rise to oscillation. Consequently, in the case of amplifiers with more than two stages, and especially those with a high input resistance, the usual precautions which are taken during the manufacture of stable amplifiers and receivers should be extended to include the input and output circuits. In order to reduce the back-coupling factor which almost always depends primarily on the distributed capacitances between the input and output circuits, various methods can be adopted. Either the input or the output circuit of the amplifier with the

corresponding conductors must be screened. At the same time, of course, the amplifier itself, or at least the stages near the screened input and output, must be completely shielded. It depends on circumstances whether the input or output is screened. If it is the output then it will be necessary to surround the whole of the cathode-ray tube with a metallic screen. This is very easily done in the case of a tube which is externally metallized over the greater part of its surface. The effective value of the distributed capacitance, due to the surface left unscreened for the purpose of observation, is small enough to

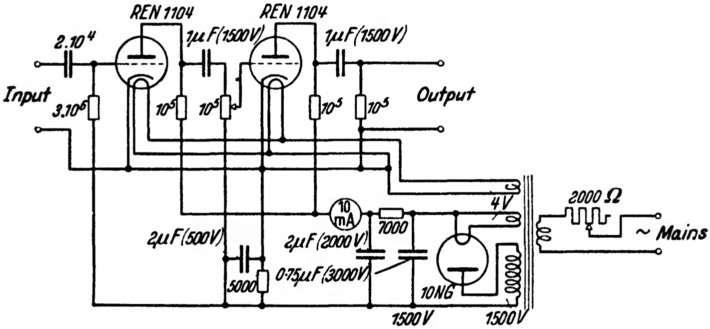


FIG. 183. CIRCUIT FOR A MAINS PRE-STAGE AMPLIFIER WHICH WILL SUPPLY 200 V. R.M.S. UNDISTORTED A.C. VOLTAGE

(Max. amplification 70; constant over frequency range 25–20 000 cycles)

be negligible. The use of stable screened amplifiers with screening of the input and output circuits enables stability to be secured with voltage amplifications up to 10^7 or 10^8 which represents the maximum demand likely to be made on the apparatus. Very much less is sufficient for the treatment of most problems. In fact, in most cases the voltage to be measured is 0·5–1·0 volt or more, and in such instances two stages of amplification are sufficient to give full deflection of the ray over the whole screen.

Fig. 183 shows a circuit and values of components for a two-stage amplifier operating entirely from lighting mains. Here, the maximum amplification is about 70 and the amplifier is linear for all frequencies between 25 and 20 000 cyc. The anode voltage of the tube is about 700; the undistorted anode alternating voltage which the amplifier can supply is therefore ample for obtaining large ray deflection with a comparatively insensitive tube. A capacitance coupling is provided at the

output as well as the input, so that fluctuations, i.e. alternating voltages, can be traced. For calibrating the amplifier, which can be carried out most simply by the method described below, it is desirable to adjust the resistance in the primary circuit

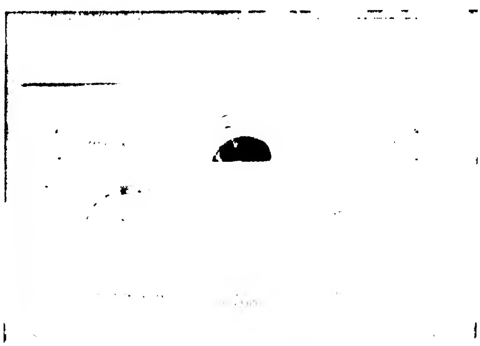


FIG. 184. EXTERIOR OF A TWO-STAGE MAINS AMPLIFIER WHICH CAN BE CALIBRATED

of the mains transformer so that the voltage is 10–15 per cent less than the mains voltage. Fluctuations of mains voltage can then be eradicated by adjusting the resistance. For correct

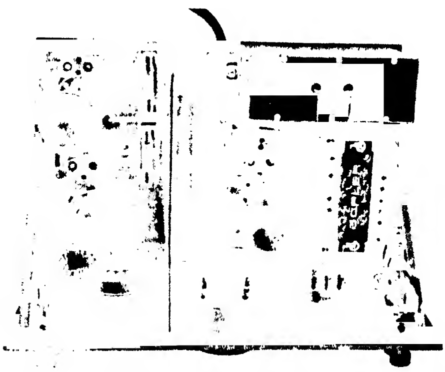


FIG. 185. INSIDE VIEW OF THE AMPLIFIER UNIT

adjustment, the anode current of both valves is measured. To fix the conditions of operation it is only necessary to adjust the anode current to that which existed at the time of calibration. An amplifier built according to the circuit of Fig. 183

is shown in Fig. 184. The interior view of the same set is shown in Fig. 185. The mains section supplying alternating voltages of 1 000 volts upwards on the h.t. side is screened metallically to exclude disturbances from the amplifying section. The compact mains amplifier described has proved efficient for laboratory operation. If the measurement of voltages less than 1 is to be undertaken, a battery-operated amplifier with the requisite number of stages in front of the two-stage amplifier described is recommended. Additional preliminary stages operated from the mains are only suitable when adequate smoothing is available. If the voltages to be measured are so small that a multi-stage preliminary amplifier is necessary to precede the final two-stage amplifier, it is extremely desirable to run the former entirely from batteries. The alternating undistorted voltages supplied by the last stage of the preliminary amplifier are, as a rule, higher than 1 volt, so that the two-stage power amplifier and the cathode-ray tube can be fully loaded. The upper limit of frequency in the amplifier of Fig. 183 can be raised to about 100 000 cyc. when resistances of $3 \cdot 10^4$ ohms capable of carrying a heavy load are substituted for the anode resistance of 10^5 ohms. At the same time, importance should be attached to the necessity for having a potentiometer of low self capacitance for controlling the amplification. The circuit for a three-stage mains amplifier is shown in Fig. 186, and differs from the two-stage unit discussed, in that the last is a push-pull stage to facilitate the supply of deflection potentials symmetrical to earth. The construction of the last stage shown should be adopted in principle for all equipment which is used in conjunction with high-vacuum tubes. It is also to be recommended for gas-filled tubes, in order to obtain the maximum sharpness of the spot and also double the output voltage. As there are, in the first stages, no voltages which are symmetrical to earth, and transformer coupling cannot be used for fear of amplitude and frequency distortion, the control voltage of the symmetrical stage is not directly available. In the circuit of Fig. 186, as also in the push-pull thyratron equipment discussed below, this is obtained as a voltage tapped from the anode resistance and fed to the symmetry stage. The division of the voltage should be so arranged that there is finally the same voltage amplitude at the grid of the symmetrical stage as at the grid of the main stage. This requirement, as also the control of the symmetrical

stage, can be met very easily by arranging for the deflection plates of the cathode-ray tube to be connected, preferably between the output terminal of the main stage and earth, or between the output terminal of the symmetrical stage and earth. Equal deflection voltages must occur in each case. Freedom from phase errors can be demonstrated by connecting the output terminals to one plate of the two pairs, while the other is earthed. A straight line inclined at 45° to the main axis

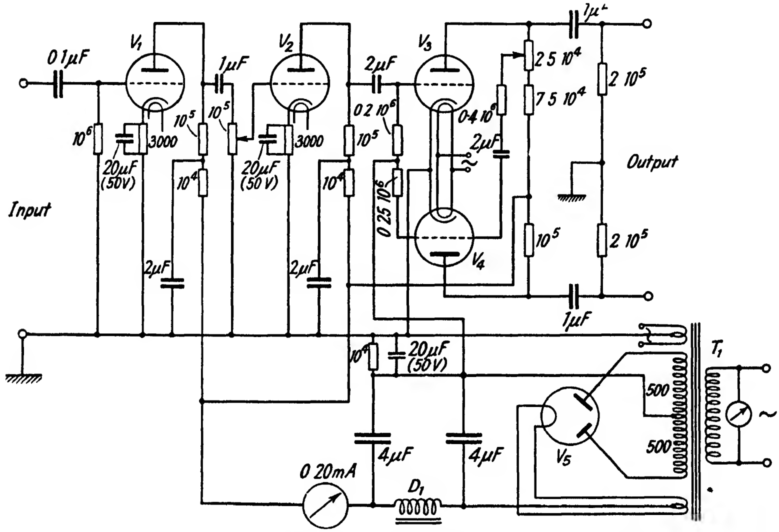


FIG. 186. DIAGRAM OF A MEASURING AMPLIFIER WITH SYMMETRICAL OUTPUT VOLTAGE.

should in general appear. An ellipse indicates a phase displacement due to incorrect design of the circuit. As is otherwise usual in this type of push-pull stage, the voltage division does not occur entirely at the anode resistance, but in the grid circuit of the symmetrical stage, the resistance being designed accordingly. This gives the advantage that the mains hum is also reduced. With this method much less smoothing than usual of the mains unit is required.

Since the amplifier and cathode-ray tube are independent of frequency down to very low limits, calibration is quite simple. Calibration of the whole equipment is possible by applying it to the amplifier and cathode-ray tube separately, but it is simpler and more accurate when the two are considered

as one unit and calibrated as such. Calibration can be carried out in several ways. If the amplifier and tube are independent of frequency down to 50 cyc., it can be done with ordinary

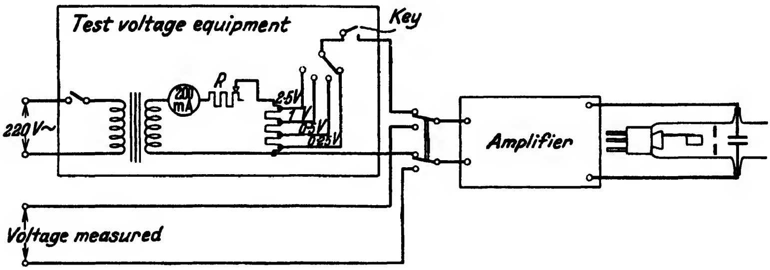


FIG. 187. CIRCUIT USED FOR CALIBRATION ON 50 CYCLES A.C. SUPPLY

alternating current measuring instruments. A simple circuit for this purpose using 50 cyc. a.c. is shown in Fig. 187. A current which can be read on a soft iron instrument is adjusted

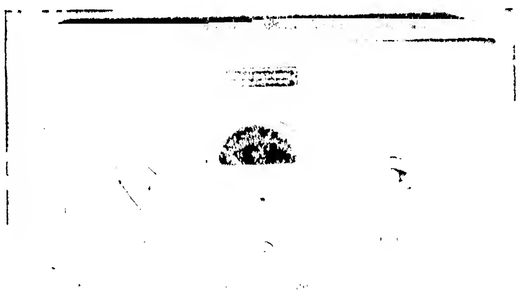


FIG. 188. VOLTAGE CALIBRATING EQUIPMENT

by a rheostat *R*, and this results in voltage drops of known values over the given resistances.

The voltages are communicated to the amplifier by the key provided. The whole calibration of the apparatus results in a definite line on the fluorescent screen of the cathode-ray tube. In order to test for the linearity which should exist if the design is correct, and in fact to calibrate for various degrees of amplification, the use of mains equipment proves satisfactory (Fig. 188). With the help of a few definite voltages

spread over a certain range the output controls provided in the various amplifying circuits can be graduated. Calibration of an amplifier control can be done even more simply, but less accurately, from the measurement of the decrease in length of the trace. Assuming linearity, this decrease corresponds directly to the decrease in amplification. Another method of calibration requiring only known direct voltages is used in the circuit of Fig. 189. Here, a direct voltage of known magnitude is applied to the amplifier input for a short time by means of the key. At the moment of depressing the key a deflection of the spot, which is easily observed, takes place, and its magnitude corresponds to the voltage at the input terminals. The period during which

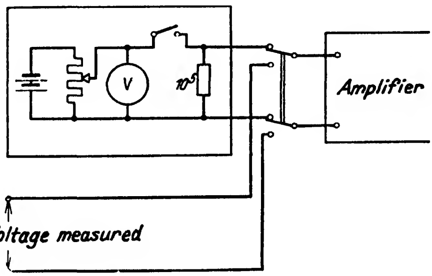


FIG. 189. CIRCUIT FOR CALIBRATION USING A KNOWN D.C. VOLTAGE

the fluorescent spot remains deflected after depressing the key depends on the time constant of the amplifier. If the lower frequency limit is at about 20 cyc., as in the case of the amplifier whose design is treated in this chapter, then the time required for the condensers to regain their initial state after equilibrium has been disturbed by the d.c. voltage is sufficiently long to permit the deflection to be observed. It is thus possible with this circuit to calibrate the unit from a d.c. source. It has already been stated that it is necessary to connect further stages in front of the preliminary mains amplifier if the voltage to be measured drops below about 0·5 volts r.m.s. The circuit of a battery-operated amplifier, which increases input voltages of 10^{-6} volt to the value of 1 volt, and maintains this 10^6 fold amplification over the frequency range 30–100 000 cyc., is shown in Fig. 190. This diagram, which shows the most suitable values, also shows which decoupling circuits are necessary to secure the specified efficiency. By the aid of this diagram, it will not be difficult to make up amplifiers with lower stage gain, the efficiency

being suited to the problem in hand. To reduce back-coupling to the input circuit which in Fig. 190 is connected to a photo-cell for the registering of rapid light fluctuations, a screen-grid valve is used in the first stage. Great care should be taken that a valve with negligible microphonic noise is used in this stage. To obtain a good frequency characteristic, anode resistances of relatively low value are used, and the

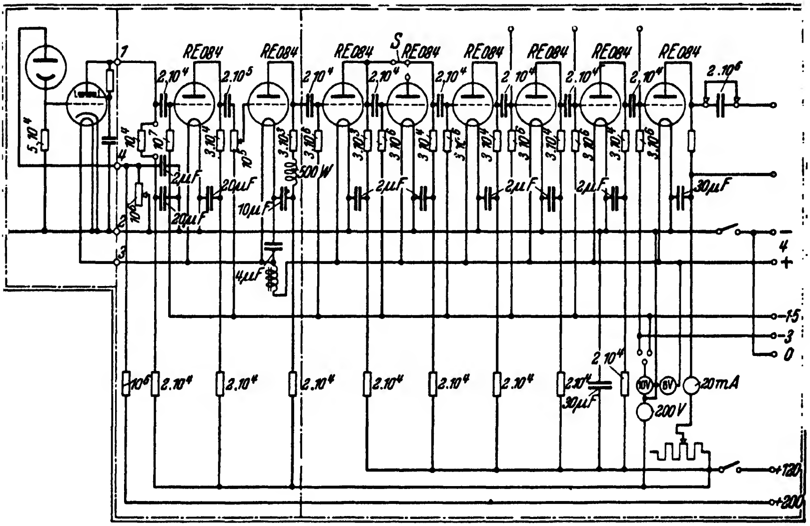


FIG. 190. DIAGRAM OF AN AMPLIFIER FOR STABLE VOLTAGE AMPLIFICATION UP TO 10^6 OVER A RANGE OF 30–10^5 CYCLES.

amplification per stage is about 8. All stages, however, are not used to this extent. An inductance is included in the anode circuit of the third stage and this, together with any capacitance available, produces a resonance effect near the upper frequency limit of the amplifier. Although this resonance is damped by a resistance of several thousand ohms also included in the anode circuit, this component brings about an extension of the frequency curve at the upper end, and so raises the range of constant amplification. A similar component can also be placed, with advantage, at the output side of the amplifier, between the last stage and the two-stage mains amplifier which may be used after it. This method of removing distortion is often used in all stages of modern television amplifiers for frequencies up to 10^6 cyc. and over. The fourth

stage of the amplifier in Fig. 190 is not used at full gain. One stage can be cut out, if desired, by the switch *S*. In order to eliminate the effect of the high capacitances introduced by this switch, the anode resistances chosen are very small. This stage serves merely as a phase reversal, which is occasionally necessary in a few problems involving measurement, and especially so in television work. In the last stages of this measuring amplifier the grid leads are also connected to special terminals which makes the cutting out of subsequent stages easier for the purpose of reducing the total amplification. Decoupling is provided

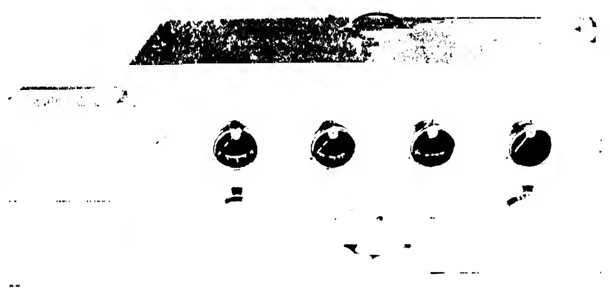


Fig. 191. Complete Amplifier with First Stage Connected at the Side

in each anode circuit of the various stages. The heating circuits of the first and last stages are also separated. It is desirable that the amplifier should be divided at the same point, and that a metal shield should be inserted to remove the possibility of back-coupling. If the amplifier is used to its full capacity, it is desirable for both sections of the unit to be operated by separate anode batteries. If it is essential, in order to amplify frequencies of less than 30 cyc., to use larger coupling condensers than those specified, the tendency to produce relaxation oscillations can be reduced by feeding the even stages from one battery and the odd ones from a second battery. A number of instruments are provided in the amplifier of Fig. 190 for controlling the operating voltage and the most important currents. The amplifier embodying the circuit of Fig. 190 is shown in Fig. 191. The arrangement of the first stage in a separate small box with connexion at the side has proved particularly useful in this screened metal box construction. In this way it is possible, without making alterations to the main amplifier,

to adjust the input circuit stage easily to the measuring problem in hand. In order to reduce the effect of mechanical vibration, which is unavoidable when the amplifier is used to the limit of its capacity, it is desirable to stand it on an inflated cycle tyre. Further details of construction of an older type of television amplifier can be seen from the interior view shown in Fig. 192.

When the amplifier is used almost to its fullest extent and the

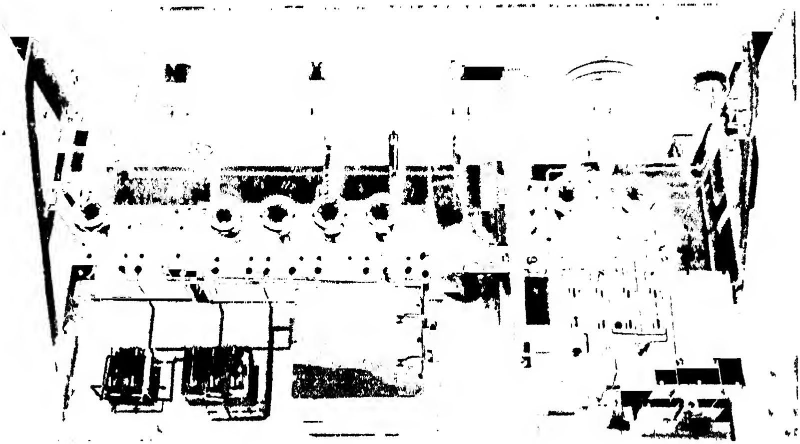


FIG. 192. INSIDE VIEW OF THE MEASURING AMPLIFIER

two-stage amplifier described above is also connected, it is possible to amplify the Schrot voltage, the level of which is about 10^{-6} volts, to 100 volts. In fact, the irregularities of the electron stream in the first stage of the amplifier have been oscillographed in this way. It is, however, unusual to load the amplifier fully. Details in the outline of small voltages can only be oscillographed if the Schrot voltage is of a second or lower order. The upper frequency limit has been raised to 10^6 cyc. by using similar circuits which differ from the amplifier in Fig. 190 in a design which is almost free from self-capacitance, and which uses high quality valves.[65] Many phenomena which undergo changes in a period of 0·00001 sec. and in which low voltages insufficient for direct deflection of the cathode ray are involved, can only be oscillographed by means of special amplifiers.

2. **Direct-coupled Amplifiers.** Coupling the amplifier stages through resistances and taking the grid voltage directly from the anode resistance of the previous stage, is the only way of amplifying very low frequencies (under about 20 cyc.), particularly in the case of slow voltage changes which extend over times exceeding several seconds (< 1 c.p.s.). The principle of the circuit of a direct-coupled amplifier is shown in Fig. 193. Each stage in this circuit has its own source of anode voltage and its own heating battery, where indirectly heated valves are not used. To ensure that the second valve receives the necessary negative grid voltage—several volts—a tapping must be provided at the source of anode current in the first stage. This tapping must naturally be selected so that not only is the voltage drop in the anode resistance compensated, but also that there is sufficient voltage in addition for satisfactory grid bias on the second stage. In Fig. 193 the pair of plates of the cathode-ray tube is connected directly across the anode resistance of the second stage. By suitably arranging the tapping on the source of anode voltage at this stage, no direct voltage will reach the plates as long as the amplifier is in the quiescent state.

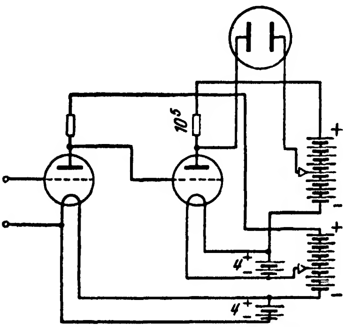


FIG. 193. FUNDAMENTAL CIRCUIT OF A DIRECT-COUPLED AMPLIFIER

Many suggestions with the object of reducing the cost of the current supplies have been put forward. In one circuit, the idea of using one d.c. source of relatively high voltage for the anode and grid circuits has been suggested. The various stages are then operated from the total voltage by means of a considerable number of judiciously placed tappings. Only a part of the total voltage is effective as anode voltage at each stage. This circuit does not appear to be very suitable for use with the cathode-ray tube for which fairly high anode voltages must be available especially in the last stage. Fig. 194 shows a simplified circuit suitable for problems such as have been mentioned. This circuit, which, with the values stated, can only be used at frequencies below 1 000 cyc., permits of further increase in amplification by a kind of resistance reaction coupling.

The back coupling arises from the fact that part of the anode resistance of the second stage is also in the grid circuit of the first stage. To secure stability and freedom from frequency distortion in the amplifier, this reaction coupling must not be made too great. Should constancy and ease of calibration of the amplifier be required, auxiliary amplification due to the reaction coupling resistance of Fig. 194 should be dispensed with and the latter short circuited. Correct adjustment of operating points is best carried out from stage to stage. It is important that the grid battery, *GB*, has such a voltage that in the last stage operation takes place at the centre of the range of control. This can be easily controlled by referring to the instrument provided in

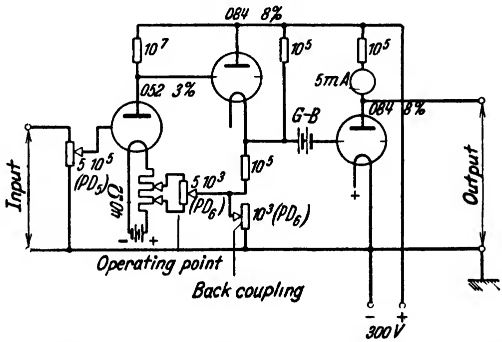


FIG. 194. DIRECT COUPLED AMPLIFIER CIRCUIT WITH RESISTANCE REACTION COUPLING

the anode circuit of the last stage. Should the operating point of the last stage vary in consequence of changes in emission, battery discharge, or as a result of a d.c. component at the input side, the correct operating point can be re-established by fine adjustment of the grid voltage of the first stage by means of the potentiometer provided. The main difficulty with d.c. amplifiers is to keep the operation of the valve at a suitable point in each stage; especially, of course, the last stage. The higher the total overall amplification, the smaller will be the changes on the input side sufficient to displace seriously the operating point of the last stage. If, for instance, in the course of measuring an alteration in the grid voltage amounting to 1 volt is available in the last stage, which is the maximum permissible with an amplification of 10^3 in the preceding stages, a direct voltage change of $\frac{1}{1000}$ must not take place at the grid of the first stage. This example shows forcibly

that with high direct voltage amplification very exacting demands are made on the constancy of the current supplies and the valves. Operation by mains equipment is not practicable when the amplification exceeds 100. The use of anode voltage from mains supply is recommended only for the last stage. Mains equipment with neon stabilizers gives more satisfactory results. A direct-coupled amplifier with high-impedance screen grid valves with two stages of neon stabilization has been described elsewhere by the author.[66] By selecting suitable valves and other components, amplification of the order of 10^4 becomes possible. In principle, mains heating for direct-coupled

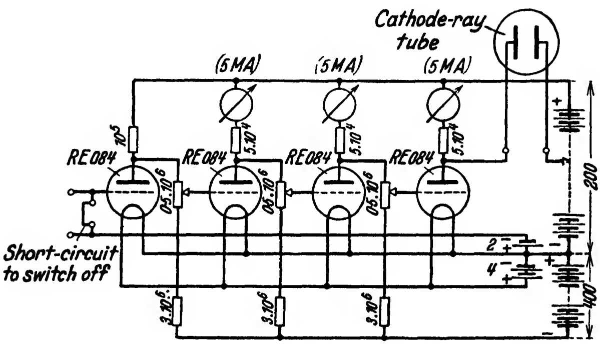


FIG. 195. VERY EFFICIENT AND EASILY ADJUSTABLE DIRECT-COUPLED AMPLIFIER CIRCUIT

amplifiers should be avoided. Indirectly heated valves give poor results even when heated from batteries, as their emission shows frequent and considerable variation. Satisfactory experience has been gained with modern battery valves, the cathodes of which have been made according to the barium vapour process and also with the older types of tungsten valves. Valves with tungsten cathodes are, of course, only used when good response is not required up to medium or high frequencies in the direct-coupled amplifier, on account of their poor efficiency. Fig. 195 shows a very useful, efficient, and easily-adjusted amplifier circuit constructed by the author. Adjustment of the amplifier is made from stage to stage. In principle, the first stage functions at the correct operating point, since the grid voltage here is definite, and no very great changes can occur owing to the low voltage measured. By adjusting the potentiometer in the anode circuit of the first

stage, the correct grid voltage of the second is so adjusted that the ammeter in the second stage shows a mean value. In the same way the third and last stages are adjusted. If any kind of fluctuation occurs in the amplifier, its cause and magnitude can be read off easily on the anode ammeter, and any readjustment necessary can be made very easily. If a large accumulator is used for heating, and secondary cells for the source of anode and grid voltages, and if arrangements are made for the heating to be switched on a few minutes before use, a constancy sufficient to enable the amplifier to be used to its full extent will result. The amplifier has a voltage amplification of about 3 000 and operates with the values given, free from frequency distortion over the range $0–10^4$ cyc. Direct-coupled amplifiers cannot be considered for amplification of the order of $10^5–10^6$ necessary in the treatment of some problems. At such high amplification, the fact that the conditions under which one stage operates affects the operation of all the other stages, and inevitably leads to fluctuations and instability, is a characteristic disadvantage. If extremely effective amplification of very low frequencies is demanded, there only remains the use of carrier current amplification which has already found many adherents in television transmission problems.(11)

A.c. amplifiers are used here. The voltage to be measured is interrupted at a frequency which is high compared with the highest frequency component in it. Mechanical methods are seldom employed. Interruption is effected most satisfactorily in the medium- or high-frequency range by means of a high-vacuum tube which is controlled by an external circuit. If high carrier frequencies are not necessary, interruption by means of thyratrons would appear to be satisfactory. In the carrier current method the a.c. amplifier must operate independently of frequency within the range limited by the sum and difference of the carrier frequency, and that of the voltage under observation. The methods of introducing the carrier frequency, in fact the theoretical and practical considerations of modulation and de-modulation, are noted in detail in the literature mentioned above. A further discussion on this point would be superfluous, since amplification by carrier frequency for increasing sensitivity is seldom used. It may be merely stated here that it is not sufficient for oscillography to select the carrier frequency so that the highest frequency differs from

the amplified frequency by two or three times. On the contrary, in amplifying for oscillography it is necessary for the carrier frequency to be at least of a higher order than the highest frequency to be amplified, in order to ensure that the carrier frequency does not appear in the oscillograms.

III. Accessory Equipment for Converting a Variable under Investigation into a Measurable Voltage

1. General. The cathode-ray tube with or without the assistance of a preliminary amplifier is capable of recording the outline of alternating voltages between 10^{-5} and 500, and can therefore cover a range of more than seven octaves. The tracing of periodically varying alternating currents of large amplitude is also possible with the cathode-ray tube. Tracing of current can be carried out directly by magnetic deflection, but in such a case the ranges of amplitude and frequency are limited as described in detail previously. The method of indirect measurement of current by means of electrostatic deflection is more general. In this case, the voltage drop across a resistance or voltage divider is oscillographed. By means of amplifiers, the range of measurement can be extended to small currents. For heavy currents, measurement is limited by the stray field from the main conductor. In all cases, precaution should be taken to see that the stray field of the circuit connected to the oscillograph shall be eliminated by suitably arranging the distance between the two or by the use of efficient screening.

The fact that voltage and current fluctuations can be recorded means that it is possible to trace fluctuations in any process, providing suitable methods of conversion are available. For instance, it is possible to trace fluctuations in the strength of high-frequency electromagnetic fields, variation in intensity of magnetic fields, changes in heat radiation, fluctuations in light, etc. It is possible to record changes in pressure and sound, small changes in length and similar variables by means of the cathode-ray tube. In order that the record shall be a faithful reproduction of the original variable characteristic, care must be taken that not only the cathode-ray tube, possibly connected to the output of an amplifier, but also the transformer which may be employed during the course of measurement, shall have linear response in amplitude and frequency over the

ranges covered. The limits set by the cathode-ray tube and amplifier, and the methods of extending these limits in any desired direction, have been discussed thoroughly above. When the oscillograph is used to full advantage it is possible to secure independence of frequency over the range 0–10^6 cyc. with ample freedom from amplitude distortion, and is sufficient for all normal purposes. In the majority of cases, frequency performance is determined entirely by the coupling transformer. Before starting to make measurements it is advisable to estimate the frequency components which exist in the circuit under observation. On such an estimate can be determined the range over which the transformer must show no frequency distortion. The accuracy of such an estimate should be checked during subsequent measurements. In order to avoid corrections, the design and dimensions of the transformer should be chosen so that it has the required frequency characteristic. As also in the case of frequency, so the upper and lower limits of amplitude should be estimated. With regard to the upper limit, tests should be made to see whether the transformer already has non-linear characteristics. Tests should be made in respect of the lower limit to see whether the measured amplitude under observation is large (at least ten times) compared with the disturbing amplitudes. In principle the amplitude of unavoidable disturbances cannot be reduced below 10^{-6} volts, since this value is determined by the transmission of electrons in the first stage of the amplifier used. (Schrot effect.)

2. **Voltage Dividers.** In principle, voltage dividers of very varied forms are used in the tracing of all kinds of electrical and other phenomena. Fundamentally, voltage dividers consist of circuit combinations of resistance, inductance and capacitance. To secure the widest frequency range, it is desirable that voltage dividers should be made entirely of non-inductive resistances, capacitances or inductances. In practice, however, pure ohmic, inductive or capacitive voltage dividers cannot be produced. How far the effect of resistance components is going to be detrimental must be estimated or tested before work is started. The most appropriate form of voltage divider is that consisting of non-inductive ohmic resistances. The advantage of the ohmic resistance divider lies not only in the fact that the division is the same for low, medium and high frequencies—provided it is suitably designed—but in addition the load on the divider remains constant. This is of

particular importance when the divider is used in conjunction with a source whose internal resistance is not very small compared with the total resistance of the divider. This is, for instance, the case in amplifiers where resistance dividers are primarily used for adjustment. The disadvantages peculiar to the resistance divider are apparent on the one hand from its construction, and on the other from the space occupied in the circuit.

The following are some types used as voltage dividers: wire resistances, fluid resistances and, particularly, the high resistances composed of a thin layer of conducting material, generally fixed to a ceramic base. Nearly all resistances change in value with high voltages or currents unless provision is made to secure constancy by increasing their length and thereby the radiating surface. With large division of resistance partial shorting may be expected owing to the parallel capacitance. For instance, when the capacitance of the amplifier is 20 $\mu\mu$F. and a frequency range up to 100 000 cyc. is required, the resistance divider must not exceed 30 000 ohms. With smaller resistances, the self-induction which causes an increase in resistance in the higher frequency range is serious. By using thin resistance wires, possibly bifilarly arranged, divided resistances of several ohms which are independent of frequency up to 10^6 cyc. can be produced. If large ratios of division are required for special purposes, and if these are to be independent of frequency over a wide range, they are best obtained by connecting several dividers in series instead of using one unit. By welding the resistance wires in such cases directly to the previous unit, dividers which are constant up to 10^7 or 10^8 cyc. can be produced.[(12)] Capacitances must be reduced to a minimum if it is feared that frequency distortion may result from their existence. This can be done by using short connecting leads, valves with spaced grid leads in the first stage, and also by employing low-capacitance supports. The capacitance in parallel with the high resistance of the divider can be reduced by screening all conductors to one end of the resistance, in which case the capacitance of the large resistance decreases and only the capacitance which is in parallel with the total divider, and which is usually of no importance, is increased. This method is shown diagrammatically in Fig. 196. The capacitance in parallel with the large resistance is reduced to a fraction of a centimetre by the

screening, which should be extended to the end of the resistance. Values of several hundred thousand ohms can, therefore, be used as the main resistance when independence of frequency up to 100 000 cyc. is required and of 10^4 ohms up to 10^6 cyc. For many purposes where constant regulation is desired, good service may be obtained from the potentiometers used in high frequency work which can be obtained in practically any size. Resistances of semi-conducting material, particularly those with insulated covering, should be used instead of wire wound resistances. Capacitive voltage dividers are mainly used where independence of frequency is required over a wide high-frequency range. The arrangement is of practically no value for low frequencies, since the reactance of the condensers becomes large enough to be comparable with the unavoidable leakage resistances. The capacitive divider is used down to 50 cyc. only under conditions of large division, i.e. particularly where measuring high voltage where relatively high capacitive dividers are possible and in fact necessary.

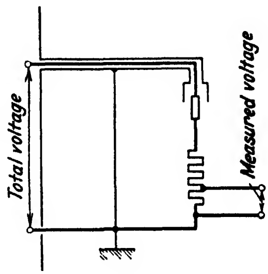


Fig. 196. Non-inductive Resistance Voltage Divider with Screened Leads

On the other hand, if the capacitance from which the measured voltage is to be taken is small—and this is frequently the case in high frequency work—the change in capacitance, which results from the addition of the grid-anode capacitance of the valve in the first stage, must be negligible, i.e. a screen-grid valve must be used or the first stage omitted entirely.

The same procedure is recommended for resistance dividers whose values exceed 50 000 ohms, because the apparent value of the grid resistance due to anode reaction is frequently of this magnitude.[(13)] One disadvantage of capacitive and inductive regulation is the fact that the frequency and the load are not independent of one another, and this can only be ignored when either the resistance of the source is very small or the total resistance of the divider very large. Conditions are particularly uncertain when, in order to secure constant regulation, one of the two capacitances of the divider is variable, and the divider then constitutes a load which depends on the way the division is made. Variations in load

with respect to the conditions of division can be compensated by special construction of the regulator.[14] Fig. 197 shows a capacitive voltage divider as used by Vieweg and Pfestorf [15] for tracing the secondary voltage curves of high-voltage test transformers by means of the cathode-ray tube.

The spherical condenser belonging to a Haefely peak value [16] measuring equipment which consists of a sphere of 750 mm. diameter, carrying the high voltage, and a hemisphere forming the measuring circuit, constituted a high voltage air condenser. The capacitance in this case at a distance of 60 mm. (for voltages up to about 70 kV.) amounted to about 10 $\mu\mu$F. and at a distance apart of 300 mm. (for voltages up to about 350 kV.), 2·5 $\mu\mu$F. Condensers of the low voltage, mica type whose capacitances could be varied between 1 000 and 25 000 μF. were used. The self-capacitance of the deflecting plates with conductors amounts to only a few $\mu\mu$F. and can be ignored. A surge-arrester protects the low voltage condensers and the cathode-ray tube. Voltage dividers consisting of pure inductances are relatively of little importance, since their range of use is very limited and they exhibit various fundamental disadvantages associated with circuit design. In practice, the most important of these is the fact that as a rule the voltage division and the position of the tapping are not linearly related to each other, and the division is therefore uncertain. In addition, owing to self-capacitance and additional circuit and tube capacitances, dividers of this type exhibit resonance phenomena, which may be within or not far removed from the upper limit of the frequency of the circuit being measured. Inductive division is also unpopular through the necessity of finding the point of self-resonance and ascertaining to what extent resonance affects the calculated ratio of division in the frequency range concerned. Furthermore, the inductive divider is more difficult to calibrate than the pure ohmic or capacitance divider. The use of inductive dividers is limited practically to oscillatory circuit devices, where a tapping on the

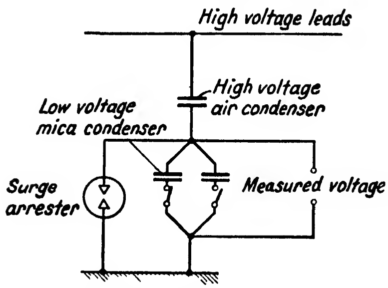


FIG. 197. CAPACITANCE DIVIDER FOR HIGH-VOLTAGE MEASUREMENTS

self-inductance fixes the desired division with certainty, when the input resistance of the amplifier or oscillograph connected is large compared with the impedance of the divider at the frequency in question.

Calibrated couplings possess similar disadvantages and yet these, especially in the forms designed by E. Klotz,[17] have gained some importance where very wide divisions ($10^6 : 1$ or more) are required, as for instance in receiver measurements. In spite of this, it would appear that when wide divisions are necessary several resistance or capacitance dividers in series have recently taken the place of calibrated couplings. It is absolutely essential when making wide divisions, that the greatest care must be taken to see that coupling from the high voltage side to the divided voltage side does not take place. As soon as the ratio exceeds 100 : 1, separation in position, or even better careful screening of the high voltage side from the divided voltage, should be arranged to avoid the production of uncontrollable disturbances. Finally, with extremely high ratios, two or three screens placed inside one another become necessary. The forms of calibrated inductive couplings indicated, are hardly of any value in oscillography. The required freedom from frequency distortion can, in their case, only be attained by introducing excessive damping, as a result of which their performance is greatly affected simultaneously. Moreover, owing to the presence of iron cores, freedom from amplitude distortion cannot be secured.

3. **Measuring Transformers for Coupling Magnetic or Electromagnetic Fields.** The production of measurable voltage from pure electrical a.c. fields has already been discussed above under the remarks on capacitive voltage dividers. The circuit and method of measurement to be used for examining a.c. magnetic fields depends greatly on the strength of the fields in question. The simplest method of measuring consists in allowing the field to act directly on the cathode-ray stream. Further details of such methods are to be found in the section dealing with magnetic deflection and also in a later part of the book. A different method suitable, however, only for field strengths above about 10 oersted max. is the use of a magnetron in the first amplifying stage. Here, also, direct magnetic influence on the electrons in the tube takes place.[18] The use of a search coil of small dimensions would appear most suitable for exploring the field from point to point, and for those not

covering a wide area.[19] The alternating voltage V_f induced in the search coil at a field strength H amounts to

$$V_f = 4{\cdot}44 \,.\, f \,.\, n \,.\, \mu \,.\, H \,.\, A \,.\, 10^{-8} \text{ volts} \quad . \quad (43)$$

where f is the frequency, n the number of turns in the coil, μ the permeability, and A the area of section of the coil ($\mu = 1$ for coils having no iron).

Since in order to secure as great a freedom as possible from frequency distortion, the self-inductance and capacitance of the coupling coil must not be great enough for the resonant frequency to approach the frequency under observation, the number of turns, and therefore the induced voltage is limited. Consequently, in the examination of weak fields, the use of amplifiers is practically always necessary.

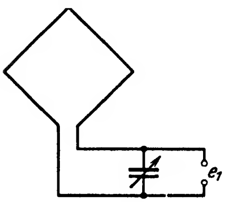


FIG. 198. TUNED FRAME ANTENNA FOR OBTAINING H.F. VOLTAGES FROM ALTERNATING ELECTROMAGNETIC FIELDS

For very large magnetic fields, a bismuth spiral as a coupling unit can also be used, the changes of resistance of which in the alternating field are oscillographed as current fluctuations in the usual way. The bismuth spiral can only be used as a coupling device up to frequencies of 10^4 cyc. as a maximun. A pronounced directional effect is present with the various coupling transformers mentioned here, particularly coils in which voltages are induced. This directional effect enables the configuration of the lines of force to be understood. In order to obtain the correct value of field strength, the exploring coils should be oriented so that the induced voltage is a maximum. The field under examination will be generally much less intense than a magnetic field since the source of radiation will usually be at a considerable distance from the place where the tests are made. The use of resonant phenomena is therefore recommended when using search coils (see Fig. 198). In the case of high-frequency fields, a frame antenna which is readily accessible for calculation serves best as a coupling transformer. Open antennae are recommended only in cases where measurement of relative values and not absolute field strengths are sufficient. The e.m.f. induced by an alternating-electromagnetic field E (volt/metre) in a receiving frame aerial with surface F and number of turns n at a carrier wavelength λ, is

$$v = (2\pi nF/\lambda) \,.\, E \text{ volts} \quad . \quad . \quad . \quad (44)$$

Tuning the frame circuit to resonance with a damping decrement d gives a voltage v_1 in the amplifier given by

$$v_1 = \frac{2\pi nF}{\lambda} \cdot \frac{\pi}{d} \cdot E \text{ volts} \quad . \quad . \quad . \quad (45)$$

With frame aerials as used for radio reception, the resonance voltages have magnitudes from 10^{-5} volts to 1 volt according to the strength, distance and transmission at the time. In order to obtain undistorted oscillograms of sudden changes in field strength, the inertia of the apparatus for measuring these changes must be sufficiently small. This is the case when the resulting half-wave band of the measuring equipment consisting of tuned aerial circuit and possibly tuned amplifiers is large compared with the frequency band which, due to fluctuations in field strength, exists near the carrier wave. For instance, if the fluctuations in field strength occur in times less than 10^{-4} sec., i.e. if the side-bands are more than 10^4 cyc. distant from the carrier wave, care must be taken possibly by additional artificial damping of the circuit that the half-wave band approximates to 10^5 cyc. In view of the way in which the wave bands are occupied to-day, it is naturally only possible to make measurements which are free from disturbances with such half-wave bands when other transmitters are not operating in the range in question, or when the field strengths to be measured are many times greater than the fields due to the disturbing transmitters. The practical construction of calibrated equipment for measuring field strength with frame and relatively large half-wave bands has been discussed already in detail elsewhere.[20]

The high-frequency signal obtained is comparatively seldom oscillographed directly. In cases where this does occur, careful screening, of multiple type if necessary, should be applied to the tube, the coupling oscillatory circuit which may possibly be used between the amplifier and the tube, and to the amplifier itself to prevent back-coupling between the output and input side of the measuring circuit. Otherwise self-oscillation or errors in measurement will occur. These troubles can, to a certain extent, be overcome in employing an intermediate frequency. However, the linear relation between input and output voltage which may be affected in the intermediate frequency range must then be controlled. In most cases, it will suffice to oscillograph the rectified h.f. current. If the rectifier

has a linear characteristic over the range covered, the oscillogram of the rectified output will show a true reproduction of the modulation of the h.f. Of course, this assumes that the highest modulation frequencies are not affected by the rectifier. Anode bend rectification is most suitable for linearity and freedom from frequency distortion when there is sufficient pre-amplification of the h.f. voltage to ensure high enough amplitude at the rectifier. The theoretical principles of anode-bend rectification have been dealt with in detail by Ollendorff.(21) The particular characteristics of anode-bend rectification in resistance coupled amplifiers and linear measurements under various conditions are to be found in a previous book by the author.(22) As the circuit of the amplifier (see Fig. 199) is designed according to considerations

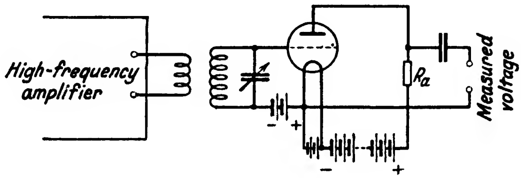


FIG. 199. CIRCUIT FOR ANODE BEND DETECTOR

already discussed, rectifiers can be made which operate independently of frequency up to 10^6 cyc. The ohmic resistance R should be selected so that it is smaller than the reactance of the parallel capacitance circuit (about 50 $\mu\mu$F.) for the highest modulation frequency. Very rapid fluctuations can be oscillographed with such rectifiers and field measuring equipment covering a wide band of frequencies. Tracing of the field strength without amplitude distortion can, as stated above, only be made when the resultant high-frequency voltage at the rectifier does not fall below a certain minimum value. In the same way as the modulation curves of h.f. waves are determined, the modulation of waves in the corresponding frequency bands, i.e. heat and light waves, can be determined.

Modern equipment generally uses specially designed diodes for the purpose in question. When using such valves, h.f. amplitudes of from 1 volt r.m.s. upwards suffice for linear rectification.

4. **Photo-electric Cells.** Very rapid fluctuations of heat radiation, the wavelength of which is adjacent to the electromagnetic frequency range, cannot be dealt with by such devices

as thermo elements and radiation bolometers which are frequently used in other measurements of heat radiation, since the inertia of these devices is many times greater than the time period of the process to be measured. For slow fluctuations, recording is more simply carried out by reflecting galvanometers than by cathode-ray tubes. Only alkali metal cells are suitable for tracing rapid fluctuations. Not only in the infra-red region, but also the visible and ultra-violet radiation, recording can be made in this way according to the spectral range of the type of photo-cell employed. The photocells used are those whose action depends on the internal or

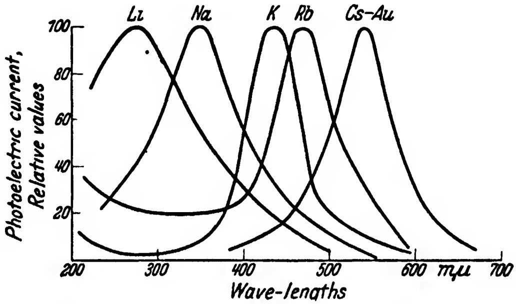


FIG. 200. CURVES OF SPECTRAL PHOTO SENSITIVITY OF THE ALKALI METALS

external photo-sensitive properties or on the barrier layer effect.[23] The peak of the sensitivity range can be displaced towards a desired part of the frequency range by suitable choice of metal as cathode and the method of sensitizing. The sensitivity curves of the alkali metals are given in Fig. 200 (taken from Fleischer-Teichmann). It will be seen that with a suitable coupling measurements in the range 200 mμ. to 600 mμ. can be covered by suitable selection of cells. Of the alkali metal cells, the caesium cathode is particularly suitable for recording in the red or infra-red portion of the spectrum, but the barrier layer cell is also used. The vacuum-type alkali metal cells are distinguished by high internal resistance and can be adapted directly to the input resistance of an amplifier, whereas the barrier layer cells have very low resistance (500 ohms), so that to secure satisfactory operation coupling through a transformer is essential. The barrier layer effect is generally observed on the boundary plane between

copper and cuprous oxide. Much greater efficiency is obtainable with more recent cells in which a conductor and a semiconductor are in combination. In this connexion, special mention may be made of the selenium barrier layer cells of W. Schottsky[24] and B. Lange.[25] The selenium barrier layer cells possess rather higher internal resistances and give voltages of about 0·3 volt per lux, so that amplifiers can be connected directly to these cells. In contrast thereto, a cuprous-oxide "front-wall" cell has an e.m.f. of about $0{\cdot}25 \times 10^{-4}$ volts per lux, and a cuprous-oxide "back-wall" cell a slightly lower e.m.f. The limit of wavelength for the selenium barrier layer cell is about 850 mμ, and for the cuprous-oxide cell about 1 400 mμ.

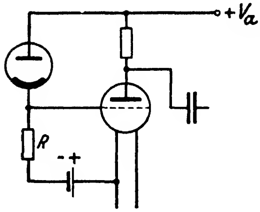


FIG. 201. INPUT CIRCUIT FOR ALKALI METAL CELLS

So far transformer equipment which will operate with sufficient freedom from inertia for still longer heat waves is not possible. Fig. 201 shows the usual circuit for an alkali metal cell, and a typical circuit for a barrier layer cell is given in Fig. 202. Frequency response and the range over which the cells have linear characteristics depend on the values of components of the circuit. The inherent internal inertia of

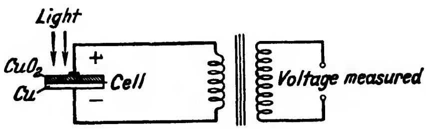


FIG. 202. CIRCUIT FOR BARRIER LAYER (SPERRSCHICHT) CELLS

the cell cannot, of course, be compensated in the circuit, and we will therefore consider it next. The release of the electrons and their passage across the boundary surface takes place in less than 10^{-8} sec., according to measurements made by E. O. Lawrence and J. W. Beams.[26] High-vacuum cells with alkali metal cathodes which involve only the stream of electrons are free from frequency distortion up to 10^7 cyc. Unfortunately the sensitivity of high-vacuum cells is relatively low (10^{-7} amperes per lumen) compared with the sensitivity of gas-filled cells (10^{-5} amperes per lumen). For this reason gas-filled cells are generally used. The sensitivity and frequency characteristic of a gas-filled cell depends to a great extent on the

applied voltage. The sensitivity, as shown by the measurements in Fig. 203, increases considerably just below the glow discharge potential. It is not, however, advisable to operate the cell at this point since the glow voltage itself is not constant, but is influenced by external factors (temperature variations). To secure stability of operation the applied voltage should be at least 10 per cent lower than the glow voltage. It is very detrimental to allow the glow discharge to pass for any length of time, especially if there is no resistance in the circuit to limit the current. Increased sensitivity due to gas-filling increases with applied voltage for light fluctuations which are below 10^4 or 10^5 cyc. Fluctuations which are more rapid than the process of ionization in the gas result only in a slow increase in sensitivity with rising voltage. Fig. 203, curve II, shows characteristics obtained by the author which confirm the behaviour mentioned. According to these measurements, the gas-filled cell behaves like the vacuum cell for high frequencies (over about 3.10^5 cyc.). Between this point and 10^4 cyc. the sensitivity does not decrease regularly, but passes through several maxima with decreasing amplitude. The reason for this, which was first investigated by F. Ollendorff,[27] may be similar to that of frequency in brightness control and deflection of gas-filled cathode-ray tubes. If the requirements are high sensitivity and as little frequency distortion as possible up to 10^5 cyc., photo-cells with argon filling to which reference was first made by F. Schröter are recommended.[28]

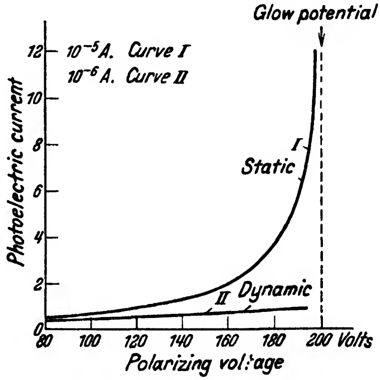


FIG. 203. RELATION BETWEEN APPLIED VOLTAGE AND PHOTO-ELECTRIC CURRENT—WITH A GAS-FILLED CELL AND A LIGHT FLUX OF 1 LUMEN

(Measurements taken under static and also under working conditions (light modulated at a frequency of 10^6 cycles)

Further details concerning alkali metal photo-cells, their manufacture and their frequency characteristics can be obtained from a book by Simon and Suhrmann.[29] Barrier layer cells also have internal inertia which is masked by the dependence on frequency which perforce is a characteristic of

the circuit owing to the high self-capacitance of these cells. Alkali metal photo-cells, as shown in the circuit, represent sources whose internal resistance depends on the intensity of the light. With the light intensities and type of cell met with in practice, the internal resistance is of the order of 10^7–10^8 ohms. If slow fluctuations of light are to be recorded ($<$ 1 000 cyc.) where the capacitance of the cell, and amplifier input and the apparent ohmic resistance of the input circuit of the amplifier are of very high order, it is possible to use leaks (R in Fig. 201) of the same magnitude. For optimum efficiency, the design of the amplifier should be such that the value of the resistance is suitably matched to the internal resistance of the cell. In most cases, where light fluctuations of very much higher frequency are to be recorded, this cannot be done. In fact, the resistance R has to be low compared with the internal resistance of the cell. Even with careful circuit design and normal valves and cells, the unavoidable capacitance is of the order of 20–30 $\mu\mu$F. In spite of the most compact construction, even in a single bulb, and with reduction of anode reaction, it is scarcely possible to reduce the self-capacitance of the cell to less than 10 $\mu\mu$F. The leak resistance must not exceed the reactance of the input capacitance for the highest frequency in the voltage to be measured. This is subject to the condition that the resistance component resulting from anode reaction in the grid circuit can be regarded as being large compared with the capacitance components, this condition being secured, for instance, by the use of screen-grid valves. For example, if the input capacitance amounts to 20 $\mu\mu$F., and the highest frequency to be considered is 10^5 cyc., the leak resistance must not be greater than 75 000 ohms. The higher the frequencies to be taken into consideration the smaller are the resistances and the less the resultant voltages across the leak resistance due to the feeble photo-electric current. The reduction of the sensitivity of the cell due to internal inertia, discussed above, on the one hand, and the external circuit which is getting away from its theoretical optimum value, results in rather poor efficiency for light fluctuations of high frequency.

Very soon the limit of amplification is reached owing to the Schrot effect. Registration of high-frequency light fluctuations free from distortion is only possible, therefore, when powerful light sources can be used. If the light fluctuations of high

frequency are confined within a narrow range of frequencies (width 5 000 cyc.) the conditions are more favourable, and the objectionable capacitance of the input circuit can be made part of an oscillatory circuit. In this case, the resistance R of the circuit of Fig. 201 should be replaced by an oscillatory circuit, the natural frequency of which should be the same as the carrier frequency of the light fluctuations. It is possible with half-wave bands of 5 000 cyc. to maintain resonance resistances of the order of 10^5 ohms in the high-frequency range. In the case of barrier layer cells with low internal resistance, coupling by means of a transformer is necessary (Fig. 202). In selecting a suitable transformer, care should be taken that the apparent damping of the cell resistance still maintains a sufficiently good frequency characteristic. The greater the frequency range required, the smaller must be the transformer ratio. The use of transformer-coupled amplification has repeatedly been the subject of detailed discussion.[30] The use of a transformer introduces the possibility of distortion due to variable permeability of the iron core. Certain other points must be considered in respect of alkali metal cells in order to get registration of light fluctuations which have to be free from amplitude distortion. The characteristic of the cell, i.e. the curve showing relation between current and illumination for low values of light intensity, is convex to the x axis up to 10^{-2} lumens. Compare the characteristics of Fig. 204 which were taken at various applied voltages (from the *Handbuch der Bildtelegraphie und des Fernsehens*, by F. Schröter). Furthermore, the curve is straight up to about 10 lumens and at higher intensities it even curves towards the x axis in consequence of saturation. The photo-cell characteristic, therefore, is analogous to that of a valve. In order to trace the light fluctuations without distortion, the operating point must be as nearly as possible at the

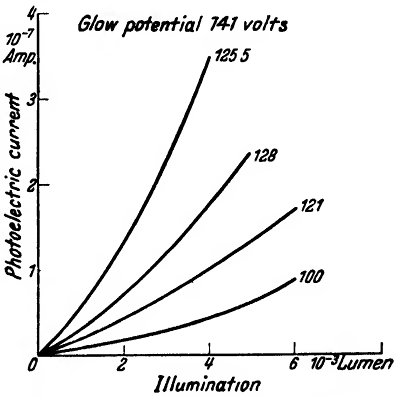


FIG. 204. CHARACTERISTIC OF THE PHOTO-CELL AT VARIOUS APPLIED VOLTAGES FOR FEEBLE LIGHT INTENSITIES

centre of the linear portion of the characteristic. The mean values of the light fluctuations to be investigated frequently do not correspond to the optimum light intensity for the cell. The latter is usually smaller. In addition the light fluctuations sometimes have a zero value as the lower limit. The most favourable position of the operating point can be varied and amplitude distortion, which would normally occur at low exposure times, can be avoided by the addition of a priming illumination consisting of a constant source of illumination.

5. **Switching Arrangements for Mechanical Oscillations.** Electric, magnetic and electromagnetic phenomena have been transformed into measurable voltages by the auxiliary apparatus so far discussed. In these cases, it was necessary to choose suitable arrangements according to the magnitude of the variables involved. The following sections deal with the conversion of mechanical into electrical energy. A problem which frequently recurs is that of converting mechanical oscillations directly into alternating voltages. Electrical pick-ups are a characteristic example of this kind of conversion. They can be used, not only for problems which involve the transformation of the lateral undulations in the track, but also in some cases the variation in depth of the grooves into corresponding voltage fluctuations, but are also suitable for registering the degree of surface roughness. This latter procedure can be carried out by moving the needle of the pick-up over the surface to be investigated at constant velocity. Normally a pick-up usually consists of a light iron armature freely suspended and held in a heavy housing. The conversion of the mechanical vibration generally takes place by the position of the armature altering the permanent magnetic flux penetrating a coil. Less frequently, the conversion results from a change in capacitance. Pick-ups very often vary considerably in their performance according to the amplitude and frequency involved, so that care must be taken when using them for making measurements. Their frequency range is limited by two characteristics, that of the armature resonance and of the housing resonance. By using armatures of very small mass and great rigidity—which applies also to the needle—the armature resonance can be raised to 8 000–10 000 cyc. as an upper limit. On the other hand, housings of large mass and inelastic mounting of the armature enable the lower frequency limit set by the housing to be reduced. Furthermore,

in order to secure good frequency response in the intermediate ranges, both resonances should be reduced considerably. This, of course, results in lower sensitivity and often occurs with pick-ups of reputable makes. With insensitive units the pick-up voltages are very seldom less than 10^{-2}–10^{-3} volts, so that amplification free from disturbances presents no difficulty. The way in which commercial pick-ups depend on frequency, and to some extent on amplitude, has been made the subject of a more detailed investigation.(31) The theory involved in calculating details of the pick-up arrangements has also been treated in a special work.(32) With the best commercial pick-ups it is possible to secure undistorted frequency and amplitude performance in the range 100–10 000 cyc. In general, the pick-up will be used to follow the conducting groove made by the usual sound-recording equipment. The measurable voltage obtained will more or less exactly correspond to the outline of the original vibration according to the distortion introduced by the linked members taking part in the tracing and to the quality of the pick-up. On the other hand, if the pick-up is used, for example, to determine the roughness of polished or treated surfaces, the voltage measured will not be a replica of the inequalities of the surface. As the voltage produced by the pick-up depends on the product of amplitude and frequency, i.e. on the so-called *velocity amplitude*, the smaller surface inequalities will be exaggerated. In order to obtain a true reproduction of the state of the surface by this electrical method, it is necessary to introduce in the measuring equipment a link which is dependent on frequency and which permits the voltage sensitivity of the contrivance to be reduced $1 : \omega$. Such variation with frequency which is exactly compensated by the distortion mentioned, can be achieved in an extremely simple way when using resistance amplifiers by connecting a comparatively large capacitance in parallel with the anode resistance in one of the first stages. The capacitance must be so large that its reactance even at the lower frequency limit of the collector is smaller than the combined resistance consisting of the coupling resistance, and the parallel circuit of the internal resistance of the valve. For this purpose, its tracing velocity over the surface must be such that the longest waves to be recorded are above the lower frequency limit of the pick-up. The point of the tracing needle must, of course, have a diameter which is less than the smallest irregularity

over which it passes. The use of pick-ups is not limited in such a way that tracing must take place continuously over fresh points of contact. It is quite possible to convert the movement of the point of one body relative to its surroundings into measurable voltages.

In this case, which has almost the same frequency limitation as the one just discussed, mechanical vibrations can be recorded in the simplest manner. Here it must be stated that when using pick-up units which only respond to deflection in one direction, it is possible to get a record of the three dimensional components from the vibrations by using tracers in the three co-ordinate directions. This resolution into components is of particular importance for the purpose of recording earthquakes, and perhaps more so for the purpose of recording pressure waves when tracing instability in the floor of the earth for geological records.

Ordinary pick-ups are, of course, inadequate for the measurement of slow vibrations such as are present, for instance, in the seismic phenomena just mentioned. In fact, it is necessary to increase the weight of the housing considerably. In this way housings with masses of several hundred kilogrammes are obtained, and with the corresponding supports the lower frequency limit is less than 10^{-1} cyc. Further details of the mechanical portion of the oscillation measuring apparatus are dealt with at length elsewhere.(33) The introduction of direct-coupled amplifiers is, of course, necessary for the registration of such slowly varying phenomena. Such vibrations need not necessarily be transferred to the conversion unit by means of a system of mechanical levers. Such systems are unsuitable for very rapid oscillations (frequencies $> 10^4$ cyc.) as already stated above. The methods described in the following section give good results in measuring mechanical oscillations of wide frequency range.

6. **Capacitive Measurement of Mechanical Oscillations.** The change in distance between a mechanically oscillating body and a fixed surface connected to measuring apparatus can be found by determining the variation in electrostatic capacitance between the two. The sensitivity of this arrangement depends on how great the change in capacitance can be made, since the fluctuations in capacitance become greater the smaller the mean distance of separation of the surfaces—the latter distance must always be kept large compared with the largest

amplitude encountered—and the greater the capacitance of surfaces opposite one another. The magnitude of the capacitance of the surfaces depends on the area oscillating in the same phase. In rapid oscillations, where only small sections of the surface usually move in phase, the measurable capacity may sometimes actually only amount to a fraction of a micro-microfarad. With slow changes of position, however, the capacitances may amount to values of 10^4 $\mu\mu$F. or more.

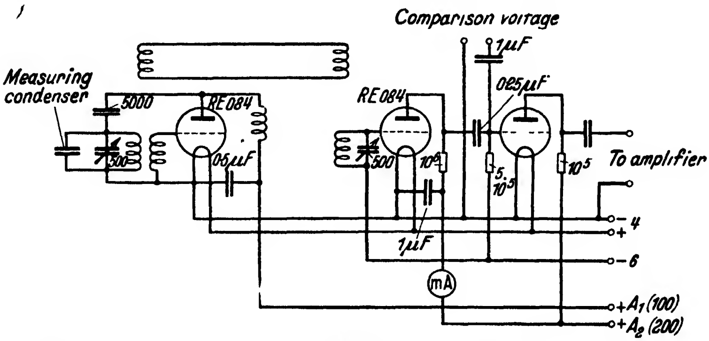


FIG. 205. H.F. CIRCUIT FOR MEASURING CHANGES IN DISTANCE

Such large capacitances can be used, for example, in measuring alterations in length due to growth in plants.

The capacitance method has the advantage that even when investigating oscillations of non-conductors, no appreciable change in mass takes place, more particularly when, for instance, the one conducting surface is produced by cathode sputtering or a similar process. The great advantage of the capacitance method consists in the ability to obtain an absolute calibration of the apparatus under static conditions in units of length by measuring the change in capacitance which occurs when the measuring electrode is moved by a micrometer screw.

A high-frequency circuit which can be recommended for measuring changes in distance, and one which is frequently used in condenser microphones, is that shown in Fig. 205. In this circuit the condenser used for measurement is in the oscillatory circuit of a transmitter, which also forms part of the measuring equipment, and this causes changes in frequency to take place. Loosely coupled to the transmitter is a further resonant circuit which is so adjusted that the static frequency of the transmitter is at the centre of the linear portion of the

rising or falling resonance curve. The magnitude of the high frequency voltage in this oscillatory circuit depends, therefore, in any particular range on the frequency of the transmitter, i.e. on the size of the measuring condenser used, provided, of course, that changes in frequency are so small that they do [illegible] overshoot the linear portion of the resonance curve. The high voltage in the second oscillatory circuit depending on the momentary value of the measuring capacitance, is rectified by an anode bend rectifier which has linear characteristic in the corresponding voltage range. Of course, fluctuations above the audible range can be recorded with the arrangement of Fig. 205, when the high frequency used is large compared with the highest frequency to be measured, and when the capacitances present do not short circuit the anode rectifier at the highest frequency. The values of Fig. 205 have been so arranged that mechanical oscillations up to 10^4 cyc. can be oscillographed. The high-frequency component in the arrangement discussed should be attenuated by the rectifier circuit to such an extent that deflections on the screen due to it are smaller than the radius of the spot. This condition will obtain to a greater extent the more remote the transmitter frequency is from the highest frequency to be measured. E. Meyer has been able to measure distances of separation corresponding to 100 mμ. with the high-frequency circuit. By filtering out the lower frequencies, the same author was successful in using the method for sound insulation measurements in spite of disturbing deflections due to mechanical movement of the walls as a result of street traffic, which exceeded considerably the amplitudes to be measured.[(34)] The method of calibration must, of course, be modified when dependence on frequency is introduced. The capacitance method is limited to cases where the oscillatory system is somewhat extended in space. The method of tracing previously described is the only one possible for examining slight charges in the distance between surfaces.

7. **Pressure Microphones.** A problem which frequently recurs in the investigation of mechanical oscillations is the determination of pressure and accelerating force. A number of accessories known as *pressure microphones* are used in such cases. Where exact measurement is not important, carbon piles, in which pressures are measured from changes in the resistance of the carbon are employed. This type of converter has the advantage that such high outputs are usually available that amplifiers

are either entirely unnecessary or at the most require only a few stages. The construction of such pressure microphones and their range of control has already been discussed elsewhere.[35] Devices in which a change in capacitance takes place by reason of a change in distance of separation are more often used as pressure microphones. The only difference between such devices and those discussed in the last section is that the movable surface takes the form of a manometer membrane. The construction of an electrostatic pressure microphone for measuring the pressure in internal combustion engines is shown in Fig. 206. The microphone is fitted with a screw thread which permits the insertion of the membrane into the plug flange of the engine.

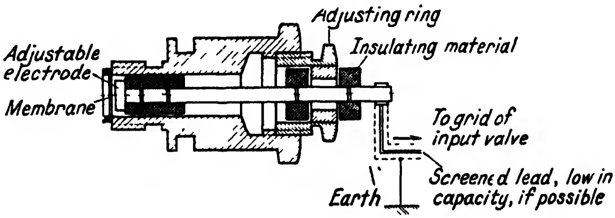


FIG. 206. CONDENSER PRESSURE MICROPHONE FOR MEASURING THE PRESSURE IN INTERNAL COMBUSTION ENGINES

In designing such pressure microphones, care should be taken that the combustion space is not greatly altered by the pressure microphone. In a few cases the pressure microphone and plug have been combined in order to investigate the pressure in the cylinder of an internal combustion engine with such a unit under actual operating conditions. The capacitive method is particularly worthy of mention here since the arrangement of the grid circuit enables it to be easily screened from the sparking circuit. Here, also, the calibration of the pressure microphone can be carried out with the assistance of manometers connected in parallel providing the circuit following is free from frequency complications. Of course, care must be taken in designing the membrane that the microphone operates according to a linear law over the desired pressure range. The natural frequency of the membrane can usually be moved towards the higher frequency range, so as to be well beyond the highest frequency involved in the measurements.

A different style of pressure microphone, which has recently been rather widely used, is a piezo-electric device. In this

contrivance the pressure to be measured is transformed by a piezo-electric quartz. The quartz is best cut in the form of a rectangular prism so that it has one face at right angles to the optical and another to the electrical axis. Pressure may be applied in the direction of either the electrical or neutral axis. In both cases voltages are produced at right angles to the electrical axis and these are applied to a direct-coupled amplifier. The form of construction of a quartz pressure chamber for a prism is shown in Fig. 207. Fig. 207 (*b*) shows a different form in which two quartz prisms are built into a steel chamber, and the whole can be screwed into the wall of

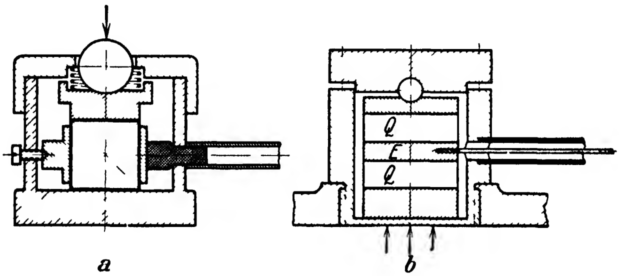


FIG. 207. CONSTRUCTION OF QUARTZ CHAMBERS FOR MEASURING PRESSURES

an internal combustion engine. Here also the direction of pressure coincides with one electrical axis of the quartz. The steel chamber has a thin base which acts as an elastic connecting link and transfers to the quartz the pressures to be measured. By this arrangement the quartz crystals are screened from electrical and magnetic disturbances as well as from dirt and temperature variations. In the bi-quartz arrangement they should be laid on one another with opposite polarity when the test electrode *E* is connected, so that the charges resulting from pressure are additive. The ball used in both constructions ensures even distribution of pressure. Details of the construction of the quartz pressure chambers described are to be found in other publications.[36] The maximum sensitivity of the indicator depends on the capacitance of the input circuit, and can be varied within wide limits by increasing the capacitance through the addition of air dielectric condensers. In practice the pressure sensitivity is of the order of 10^{-11} coulomb/kg. The resulting voltages are of the order of 10^{-3}

to 1 volt according to the magnitude of the parallel capacitance and the applied pressure. In order that the charge shall not escape even with slow pressure changes, the whole of the input circuit, consisting of pressure chamber, first stage amplifier and possibly also range condenser, must be very well insulated. To this end, the grid of the amplifying valve must be taken out separately and insulated by amber in the same way as the lead-in to the pressure chamber itself. Fig. 208 shows a special valve for the first amplifying stage of a direct-coupled amplifier for piezo pressure measurements. The arrangement, in particular the input circuit of the piezo pressure measuring equipment, is to be seen in Fig. 209. Freedom from amplitude distortion over a wide range is assured. The modulus of elasticity of quartz at $0{\cdot}8 \,.\, 10^6$ kg./cm.^{2} is so small that deformation due to pressure can be ignored. Consequently, the high natural frequency necessary for the measurement of mechanical oscillations is assured, and the quartz can be used for the registration of pressure variations up to over 10^4 cyc. By introducing smaller, specially cut quartz of low sensitivity, very much more rapid fluctuations, such as occur in measurements of ultra-short sound waves, can be converted into *voltage* variations which are free from frequency distortion. If the insulation of the input circuit is sufficiently well maintained, the lower frequency limit is low enough to permit of perfect static calibration being carried out on the pressure measuring equipment. The maximum sensitivity of the quartz apparatus is so high that considerable voltages are produced by the low pressure which results from exposure to a current of air. It is clear

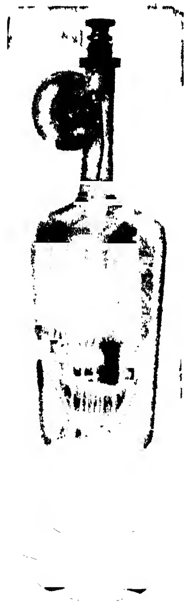


FIG. 208. INPUT VALVE FOR MEASURING PRESSURES WITH A PIEZO CRYSTAL

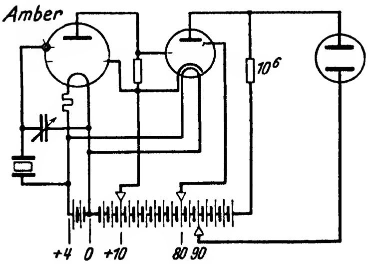


FIG. 209. COMPLETE PIEZO PRESSURE MEASURING CIRCUIT

that the same equipment can convert sound pressure into measurable voltage. In this case the piezo converter acts as the sound microphone.

8. **Acoustic Microphones.** The function of the sound microphone is to convert changes in pressure due to sound waves into alternating voltages. Freedom from amplitude and frequency distortion is more easily secured during the conversion with microphones than with other electro-mechanical devices (pick-ups, loudspeakers, etc.). The reason for this probably lies in the fact that the amount of energy converted and the amplitudes involved in absolute value are very small. In spite of this, the greatest care must be taken in selecting microphones as conversion units. Carbon microphones are most general These in the form used for telephony can at the best only be used for simple demonstration problems. In the best types the frequency range extends from about 500–3 000 cyc. Even within this limited range, there is a considerable number of peaks in the response curve. The efficiency itself is good, so that, as a rule, alternating voltages which are eventually sufficient for controlling an oscillograph at low anode voltages, are available at the output side of the transformer. The distortion factor of the microphone capsule for telephony is considerable. The noise level caused by small fluctuations of the current when passing between the carbon granules is fairly high. More detailed irformation of the properties of simple telephone microphones are to be found in a work by M. Grützmacher.(37) The simplest carbon telephone microphones are only used for demonstration purposes both on account of the imperfect properties mentioned, and also because of their fluctuating sensitivity. The contact microphones developed by E. Reisz, which are used in radio work and which are also based on resistance fluctuations between the carbon granules, function much more satisfactorily. In the Reisz microphone, sound waves exert direct pressure on the carbon powder which is placed between two rigid electrodes in a surface depression of a block of marble. The carbon powder is shielded from the outside by a thin film which does not affect the vibrations. The size of the powder particles and the area of surface sensitive to sound is selected so that, within the audible range there is as little frequency distortion as possible. In the usual design of the Reisz microphone, as in all microphones with low distortion factor, the efficiency is many times less than in telephone

microphones. The usual circuit of the Reisz microphone is shown in Fig. 210. As the resistance of the Reisz microphone is of the order of 10^2 ohms suitable matching by means of a transformer is essential, if high efficiency is to be obtained. The transformer ratio and design are selected so that good frequency response is attained over the interval 50–1 000 cyc. The voltages at the secondary side for medium sound intensities (1 microbar) are of the order of 10^{-3}–10^{-2} volts. Later a so-called *high current* type was developed which gives voltages of 10^{-1} to 1·0 volt to the amplifier input, a relatively low distortion factor being maintained for equal sound intensities. The noise level in the Reisz microphone relative to the converted sound amplitudes is much lower than in the case of the telephone microphone. It is, however, higher than in the condenser microphone and the electrodynamic microphones discussed below. Highly damped carbon microphones are generally practically free from frequency distortions from the lowest frequency up to $2 \cdot 10^4$ cyc., and the distortion mentioned is due almost entirely to the coupling transformer. If very slow changes in sound pressure, or those which lie near or just beyond the audible range, are to be recorded, it is necessary to dispense with this arrangement and provide two or more stages of preliminary amplification, tapping off the voltage to be measured across a non-inductive resistance of the order of 100 ohms. If, during the quiescent state, the current flowing through the microphone does not exceed the highest permissible value, the sensitivity of the instrument will be well maintained even over long periods. The Reisz microphone is not suitable for measurements where the highest accuracy is essential.

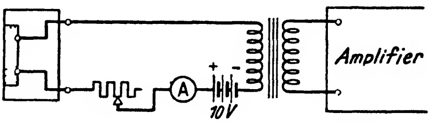


FIG. 210. CIRCUIT OF THE REISZ MICROPHONE

For precise measurements, the condenser microphone is in general use to-day. The usual form of condenser microphone consists of a light thin membrane of great rigidity whose natural frequency is as a rule near the upper limit of audible frequency. The following properties are of importance in considering the suitability of a condenser microphone for the purpose of measurement. The membrane and its support must change as little as possible during the course of time. Calibration

of the condenser microphone should be carried out some time after the membrane has been fixed in its housing, since its properties, even with the best designs, alter within certain limits during the course of the first few days. Furthermore, the construction must be so designed and carried out that the distance of separation between the membrane and the opposite electrode cannot alter with temperature changes and mechanical vibration. To secure high efficiency and adequate damping of free vibration of the membrane through the air cushion, the distance between the membrane and the opposite electrode should be kept as small as possible.

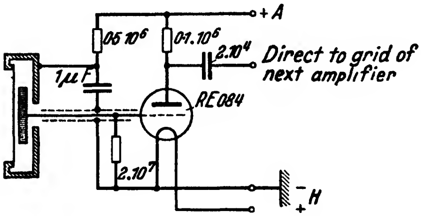


Fig. 211
Circuit of the Condenser Microphone

Parallelism of membrane and opposing electrode surfaces, which is attained only in the best designs, ensures the possibility of having the smallest separating space between the two electrodes. A circuit (Fig. 205) in which the smallest change in distance of separation of the condenser surfaces is converted into a measurable voltage has already been discussed in detail

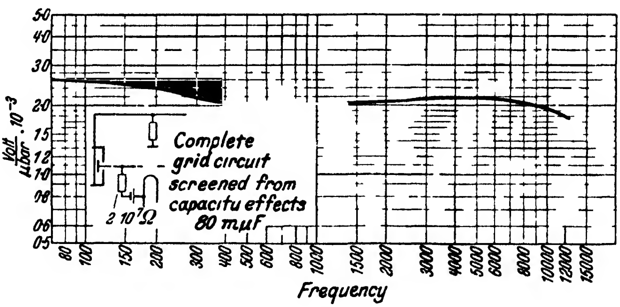


Fig. 212
Frequency Curve of a Condenser Measuring Microphone

on p. 229. The condenser microphone can be connected directly to the high-frequency measuring circuit as shown, and simply takes the place of the measuring condenser. This arrangement has the advantage of high sensitivity. It is to be recommended particularly for the measuring of very feeble

sounds or for picking up vibrations of very low frequency. Fig. 211 shows another input circuit for the condenser microphone which has been used considerably. With a given condenser microphone, the frequency curve in this case depends largely on the value of the coupling resistance, especially in the low-frequency range. Coupling resistances of $5 \cdot 10^6$–$2 \cdot 10^7$ ohms are employed, for normal microphone and circuit capacitance. If a condenser microphone is calibrated for a certain coupling resistance and a given total input capacitance, the same values must be included in the circuit employed. The calibration curve of a good condenser microphone suitable for measurements is shown in Fig. 212. The total input capacitance, including that of the microphone and grid circuits, was adjusted to 80 $\mu\mu$F. The sensitivity of the microphone is about 2 mV./μB. This is not very much lower than that of good carbon microphones. Here, however, freedom from frequency distortion is obtained over a wide range from the lowest to the highest frequency of audibility, with constant calibration factor. The condenser microphone exhibits a linear characteristic up to the highest acoustic intensities. Whereas carbon powder microphones are linear in response up to sound intensities of about 70 phon, condenser microphones can be loaded up to the extraordinary acoustic intensities of 140 phon without the distortion factor becoming serious.

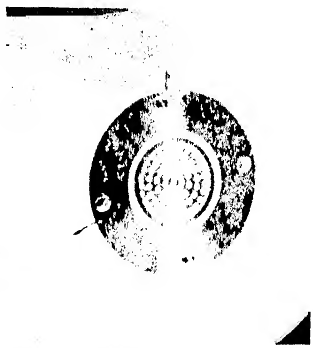


FIG. 213. MODERN CONDENSER MEASURING MICROPHONE

Fig. 213 shows the construction of the condenser microphone for measuring purposes, the characteristics of which were shown in Fig. 212. To secure high efficiency, the capacitance of the input circuit should be kept as small as possible. The condenser microphone frequently forms a single unit with the first amplifying stage. Such a construction in which the first stage is screened and built in a metal box behind the microphone is shown in Fig. 214. The impedance of the first amplifying stage is about 10^4 ohms, a value which allows the insertion of a cable several metres in length between

the microphone unit and the amplifier without the use of a coupling transformer. One great advantage of the condenser microphone shown, which has a perforated auxiliary electrode in front of the membrane, is the ease with which it can be calibrated. If the auxiliary electrode is insulated or if it can be substituted by a similarly insulated electrode, it is possible to obtain calibration (by a purely electrical method) by a steady but adjustable alternating voltage between the housing and the auxiliary electrode. It is only necessary to determine the amplitudes which are injected into the oscillograph at the various frequencies in order to determine the frequency response of the whole measuring device. The calibration which consists merely of substituting electrostatic forces for the acoustic forces which normally influence the microphone is very simple in comparison with other microphone calibrations. It is only the calibration in terms of absolute sensitivity which presents any real difficulty. Further details of this type of calibration, originated by M. Grutzmacher and E. Meyer,[38] have been published. But only the pressure curve is obtained by this method. At very high frequencies where ultimately the dimensions of the microphone are comparable with the wavelengths of the sound, the true sensitivity is somewhat higher, but never more than twice as great as that shown by the curve obtained electrically, as far as frequencies below 10^4 cycles are concerned. The true curve of the microphone measured by the electrostatic method in Fig. 212 therefore also shows a gradual rise towards the higher frequencies. In combination with normal low-frequency amplifiers which fall off a little above and below, this microphone provides almost complete freedom from frequency distortion in the audible range. Certain types of electrodynamic microphones have again become rather more widely used. They do not appear to be very suitable as

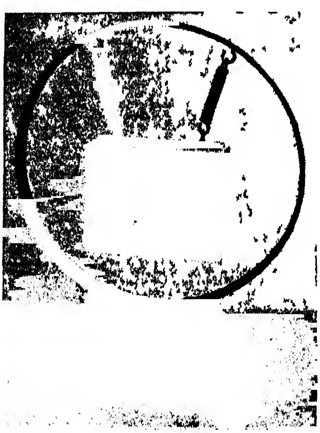


FIG. 214. CONDENSER MICROPHONE AND FIRST AMPLIFYING STAGE IN ONE UNIT FOR MAKING MEASUREMENTS

a means of conversion for the purposes of measurement in consequence of the necessity for using a coupling transformer in almost every case. In certain research problems it is necessary to have microphones available which will also convert with equal efficiency, or almost so, into measurable voltages, acoustic waves which lie above the limit of the audible range. Most microphones, such as the carbon powder and condenser types of special construction, fail at frequencies over $2 \cdot 10^6$ cyc. The inertia of even the smallest masses begins to become appreciable at such high frequencies. There are two ways of converting medium or ultra acoustic waves into alternating voltages—either the size of the vibrating masses must be reduced to a minimum—the method used, for instance, in the cathodophon—or the restoring forces must be increased to such an extent that the natural frequencies are displaced into the high-frequency range in spite of the large masses. The latter is the case with the piezo pressure receivers discussed above, the natural frequency of which can be made almost as high as desired by grinding and selecting the dimensions of the quartz. Quartz microphones are therefore very suitable for work with ultra-short acoustic waves. Unfortunately, the piezo crystal is extremely inflexible to the incidence of acoustic waves so that its response to air is not very good, which results in low efficiency of this type of microphone. Much better performance is obtained, of course, near to the resonance point. Yet even here the damping by the surrounding air is still so small that the time required to build up the vibration is comparable with the period of the low-frequency oscillation. Operation at the resonant point, therefore, is not possible in such cases where the ultra-short sound waves are modulated by low frequencies, and the piezo microphone can only be used over a certain frequency range. More favourable conditions exist when the crystal is used in fluids for the purpose of measuring sound pressures. The best-known type of microphone with very small moving parts is the cathodophon of Vogt, Masolle, and Engl.[39] In this type, the conversion into current fluctuations is effected through the use of an ionized volume of acoustically sensitive air situated between a hot cathode and an opposite electrode. The length of the air space amounts to only a fraction of a millimetre, and the voltage between the electrodes is 500 volts. In contrast to the pressure microphone discussed above, which represents a generator independent of frequency,

the cathodophon is a velocity receiver. Its sensitivity decreases therefore in proportion to the "velocity amplitude" as 1 : ω. In order to compensate this frequency characteristic a component with the opposite frequency response must be introduced. This is most simply effected by coupling the amplifier through a self-inductance, which is chosen so that its resistance at the highest measured frequencies, is low compared with the resistance of the discharge space. The corresponding circuit of the cathodophon as a sound receiver free from frequency distortion is given in Fig. 215. In this form, the cathodophon could be used as a sound receiver of good frequency up to frequencies of 10^5 cyc., i.e. until ionic inertia becomes appreciable.

The conversion of low sound pressures by the cathodophon

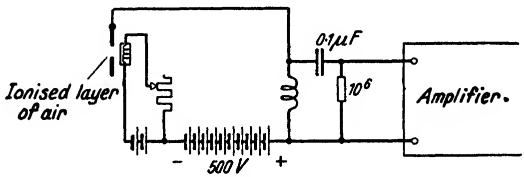


FIG. 215. CIRCUIT OF THE CATHODOPHON AS A SOUND RECEIVER FREE FROM FREQUENCY DISTORTION

or at any rate by the practical types which have become known, is not possible since the mean disturbance level of the cathodophon is very high owing to the action taking place at the cathode. As the accessory apparatus for converting any phenomenon into a measurable voltage, the amplifiers for increasing the sensitivity and the cathode-ray equipments have been discussed in the previous sections, all equipments which are necessary for the registration of the maximum values of phenomena to be investigated have been dealt with. The way in which the phenomena investigated vary with time and the simultaneous recording of this dependence in time and work co-ordinates, calls for further accessory equipment, and this makes possible a record in time co-ordinates which are independent of the work co-ordinates.

A saw-tooth oscillation circuit including a thyratron and controlled by the audio-frequency signal under examination is described by Grützmacher.[67]

IV. Time Deflection

1. Time Deflection by Rotating or Vibrating Mirrors. The basic principle of rotating or vibrating mirrors is that the inclination of the mirror to the light rays from the fluorescent spot on the screen, i.e. its angle of incidence or reflection, is altered. Owing to the rotation of the mirror whose axis is parallel to the ordinate of the oscillogram, the reflection of the fluorescent spot is made visible at various points of the mirror in turn. These images which appear subsequently are simultaneously recorded by indirect observation through the persistence of vision of the eye, or with light sensitive

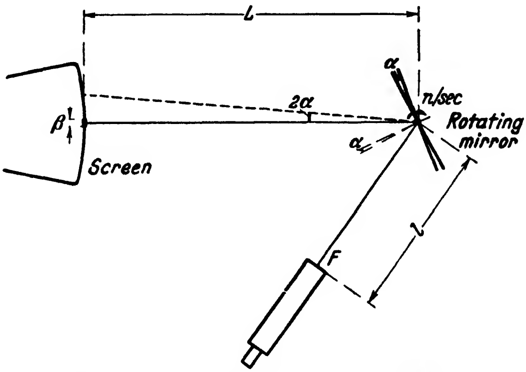


Fig. 216. Diagram of the Ray Path with Moving Mirrors

materials by photography; the stationary spot becomes a line and the spot deflected by the work process is drawn out into an oscillogram. The relative length of the time base produced is determined firstly by the angular velocity of the moving mirror, and secondly by the distance L of the fluorescent spot from the mirror which is equal to the distance of the virtual image of the spot from the mirror. The velocity of the time deflection is therefore a function of the peripheral velocity of the virtual image. At the same time, an angular change of 2α of the radius vector between the axis of the mirror and the virtual image corresponds to a change in angle α of the rotating mirror. The maximum deflectional velocity is therefore determined firstly by the maximum velocity of the mirror which is limited by its construction, and secondly by the distance L. The distance l from the mirror surface to the point of observation affects

the brilliancy of the oscillogram to be recorded. The magnitude of l is determined by an optical system, which is provided, if necessary, at this point. The diameter of a suitable objective, which may be necessary, must be visible from the fluorescent spot in order that the whole of the beam from the spot falling on the mirror may enter the optical system. The virtual image of the oscillogram can then be regarded as being enlarged by a lens system, which is important when examining patterns with relatively high frequency components. In this case, the distance between the screen and the mirror has to be increased, which results in a decrease in the size of the oscillogram and its brightness, which factors are obviously inversely proportional to L. The eye-piece must be sufficiently powerful to maintain the greatest possible brilliancy in the oscillogram. For a magnification of $\times$ 8, the diameter of the objective should be 6 cm. which, with a pupil diameter of 8 mm., allows all the light to enter the eye. Metal or glass is best for the moving mirror. Glass mirrors with a reflecting metal surface on the back give double images due to reflection at the surfaces of the glass. The intensity of the secondary image is about 5 per cent that due to the reflecting surface. In order to prevent distortion in the oscillogram, the mirror surface must be optically flat and free from striations or unevenness. It is important with mirror deflection that the fluorescent screen surface should be free from after-glow, otherwise a picture will be retained alongside of the reflections of the fluorescent spot which will produce a hazy oscillogram. With calcium tungstate an indefinite zero will appear with mirror deflection at a frequence of about 500 000 cyc. With more recent materials (e.g. No. 2) the passage through the zero point was still sharply visible at this frequency. Mirror deflection can be effected either by a single mirror vibrating with a sinusoidal frequency, or by a rotating double or multiple mirror.

Vibrating mirrors are usually supported on a bifilar suspension and excited magnetically or electro-dynamically. The maximum velocity attainable for time deflection is limited by the natural frequency of the mirror system. The mirror surface must be as large as possible in order to obtain the best optical conditions. The low natural frequency which results from this condition only permits photography of relatively slow phenomena with, say, frequencies of several thousand per second. The oscillograms photographed with vibrating mirrors show

closed curves, so called *Lissajou's figures.* Lissajou's figures are always obtained when the work frequency is equal to or a whole multiple of the time deflection frequency. Although the curve shape of the desired alternating quantity cannot be observed directly from these figures, it can be obtained easily by retracing with a known time deflection of the required value. Since Lissajou's figures are also produced by sinusoidal voltages with electrical time deflection, they are analysed here in more detail. If the amplitudes and frequencies of the time circuit and the work circuit are equal, the Lissajou figure

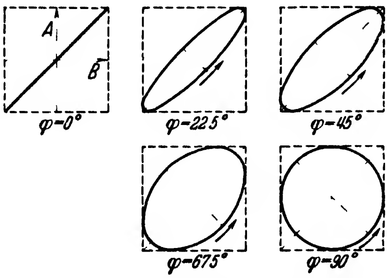


FIG. 217. LISSAJOU'S ELLIPSES FOR EQUAL AMPLITUDES BUT OF VARYING PHASES

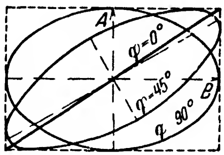


FIG. 218. LISSAJOU'S ELLIPSES OF VARIED AMPLITUDE AND PHASE

produced is an ellipse as can be seen from Fig. 217, the major axis of which is the centre line between both component directions. If the phase relationship of the two deflections changes, the eccentricity of the ellipse will alter. With a phase difference of 90° the ellipse becomes a circle. If the amplitudes are unequal an eccentric figure is also produced, but as the phase difference increases, not only does the eccentricity alter, but the major axis also rotates as can be seen from Fig. 218. The analytical relation for the elliptic figures shown in Figs. 217 and 218 results as follows [40]—

The deflections in both co-ordinates are for $\omega A = \theta$, $x = A \sin \theta$, $y = B \sin (\theta + \varphi)$, and since

$$\sin \theta = x/A$$

and

$$\cos \theta = [\sqrt{A^2 - x^2})]/A \quad . \quad . \qquad (46)$$

$$y = B[x \cos \varphi + \sqrt{(A^2 - x^2)} \, . \sin \varphi]/A \quad . \qquad (47)$$

which is the equation of the figure and can be shown to be an ellipse. This figure gives for $\varphi = 0$, $y = Bx/A$, which is a straight line inclined to the x-axis at an angle $a = \tan^{-1} (B/A)$.

For $\varphi = 90°$, $y = (B/A)\sqrt{(A - x^2)}$, or

$$(x/A)^2 + (y/B)^2 = 1 \quad . \quad . \quad . \quad (48)$$

which is the equation of an ellipse which becomes a circle when the amplitudes are equal ($A = B$).

Further, if

$\varphi = 180°$, $y = -(B/A)x$, a straight line

$\varphi = 270°$ as for $\varphi = 90°$

$\varphi = 360°$ as for $\varphi = 0°$.

If the deflection frequencies are unequal, it is true that a stationary figure results as long as the relation between the

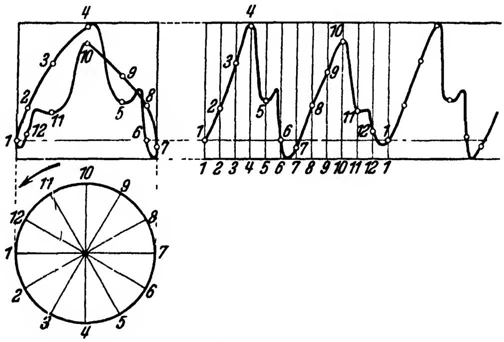


FIG. 219. ANALYSIS OF A LISSAJOU'S FIGURE BY RYAN'S METHOD

frequencies can be expressed as a ratio of two whole numbers, but the figures are much more involved than the ellipse or circle. But the graphical conversion of these closed curves into periodic time functions is obtained with relative ease, according to Ryan,[41] by introducing a sinusoidally divided scale. In Fig. 219 an example of this type of analysis has been made. A circle is drawn below the Lissajou figure (time base in horizontal co-ordinates) and its diameter is equal to the width of the oscillogram. The periphery of the circle is divided into a number of equal sections (e.g. 12). Perpendiculars cutting the Lissajou figure in the points 1–12 must be offset through the points of division. If the distances of the points of intersection from the base line are plotted as ordinates from an equally divided base line, the required curve will be obtained. Redrawing in this way results in the centre portions of the Lissajou's figures being shown more correctly than those near

the perpendiculars enclosing the figure. This fault can be eradicated by taking a second photograph with the time deflection at a different phase angle. For instance, if the photograph is retaken having its time deflection displaced by a phase angle of 90°, the portion of the curve which previously appeared at the edge will move to the centre where its lateral displacement can be determined exactly. The values from 45°–135° are then taken from the first photograph and the rest from the second.

For time deflection, the rotary method is used to-day to the exclusion of almost all other methods of actuating mirrors. This method produces direct oscillograms with linear time scale without the need for graphical redrawing. The rotating mirror has two or more reflecting surfaces. The virtual image of the fluorescent spot traverses the first reflecting surface perpendicular to the ordinate axis (Fig. 216) from left to right. As soon as the angle of incidence of the second mirror has become sufficiently small, the spot appears on the left-hand side of the following mirror surface. Synchronism between the work deflection and the time deflection will then be secured if these frequencies are equal. If n is the number of revolutions of the axis of the polygonal mirror per sec., s the number of reflecting surfaces, and f the frequency of the voltage measured, an image of one complete period is obtained when $(f/ns) = 1$. When $(f/ns) = 2$, an image of two complete periods results, and so on.

The peripheral velocity and number of mirrors must not, in the case of non-periodic and unsynchronized phenomena, be allowed to be high enough for several oscillograms to be observed at the same time through persistence of vision. In investigating high-frequency vibrations it is desirable for the axis of the mirror to be inclined periodically in order to eliminate this overlapping. In the case of photographic recording of the oscillogram, the exposure period, which for visual observation is fixed at 16 pictures per sec., can be reduced and overlapping of the oscillogram avoided by suitably adjusting the timing of the shutter. The maximum velocities of the time deflection attainable are exemplified by the following figures. A time deflection velocity of about 1 000 m. per sec. is attained when there is a very large distance between the mirror and the fluorescent screen, L being equal to 5 m., and the rotational speed of the mirror 30 r.p.s. This enables photography at a

maximum frequency of 500 000 cyc. to be carried out. An optical system is necessary for the value of L given in order to secure a sufficiently large oscillogram. The brilliancy of the spot in modern tubes is quite sufficient to enable the shape of the curve for a single high-frequency oscillation to be recognized. The quality of the rotating mirror determines the peripheral velocity ultimately attainable and also the quality of the images. The axis of the mirror must be parallel with the ordinates of the oscillogram and should generally be fixed in position, as otherwise a shift of the zero line will result and

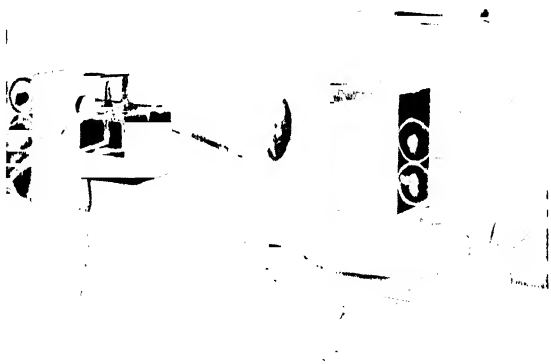


FIG. 220. ROTATING MIRROR DRIVEN BY A GRAMOPHONE MOTOR

the oscillogram will be displaced. The principles already given above apply to the mirror surface itself. For low peripheral velocities, ordinary glass mirrors with backing of mercury are used, being supported in metal frames. The inaccuracies in the geometrical arrangement resulting therefrom can be reduced considerably by metal mirrors. For high velocities metal is more suitable than glass for the mirror on account of its greater rigidity. Accurate balance of the moving parts is essential for all rotating mirrors. For tracing at very high peripheral velocities, the mirror should be enclosed in a protective wire cage to avoid danger to the observer from flying fragments should a breakage occur. If a mechanical drive is not available, rotation by hand is sufficiently good in an emergency and with practice provides fair synchronization if the velocity is not

too high. If a gramophone turntable is available (Fig. 220), the rotating mirror can be mounted on it fairly easily. The clockwork, as well as the electrical type of record drive, permits of adjustment to the rate of revolution within wide limits. As the number of revolutions of the turntable is generally fairly low, the use of gearing between the mirror and gramophone drive is to be recommended for increasing the speed of the time co-ordinate. The advantage of the clockwork drive is that it does not cause magnetic disturbances in the oscillograph. With the ordinary electric motor for driving, magnetic disturbances are usually very small. Furthermore, electrical synchronization is possible with an electrical drive. (Rotation by Synchronous Motor.)

2. **Electrical Time Deflection.** (A) PRINCIPLES. As distinct from mechanical-optical time deflection by means of moving mirrors where the deflection takes place outside the cathode-ray tube, with electrical deflection the work and the time co-ordinates are produced inside the tube by additional deflection of the cathode ray and are both carried out in the same way—through the electrostatic field of two condenser plates, or by the electromagnetic field of two deflecting coils. With electrical time deflection, a two-dimensional figure of the process traced, which is stationary in the case of periodic and synchronized phenomena, appears on the screen of the tube. All mechanical devices described hitherto are unnecessary since no moving parts are required outside the bulb. As a result, the size of the whole tracing arrangement is considerably reduced. It was due to electrical time deflection, in particular, that the use of screen contact photography for tracing very high velocity phenomena as are described below became possible for the first time. As distinct from mechanical time deflection, electrical time deflection requires merely an elaboration of the auxiliaries already used for production of the rays and deflection by the phenomena being measured.

The resolution of the time base into a time surface which is particularly important in the production of very high time velocities, also becomes possible for the first time by the insertion of a second time co-ordinate of equal or different frequency to the first. It is immaterial in principle whether the additional time co-ordinate is produced electrically inside the tube or outside mechanically. The record of the time can result as a closed figure, for instance, a polar diagram

(ellipse, circle, and so on) the shape of which is influenced by the measured voltage. Another method of tracing often used consists in making the second time co-ordinate—the velocity of which is small compared with the first one—operate in the *same* direction as the voltage to be measured.[42] It may be necessary here to provide a third deflecting system. The ray is deflected by the second time component across the oscillogram. Simultaneously it is carried to and fro at high velocity in the longitudinal direction, for instance by an undamped high-frequency or saw-tooth oscillation. The time deflection occupies the whole surface of the oscillogram in which the lines of the first time deflection lie more or less close together according to the velocity ratio. The creation of the deflecting fields for the production of a time surface is best carried out by a double saw-tooth oscillation equipment as for television. The combination results in a very long measuring period per oscillogram as compared with ordinary methods of deflection. If the work process is not recorded by deflection but by intensity modulation of the cathode ray, the time surface becomes a line raster of television technique. Most electrical time deflection devices used to-day are based on the principle that the back and forward traverse of the fluorescent spot on the time base is caused by a sinusoidal or saw-tooth oscillation applied to the time deflection plates. Whereas with sinusoidal oscillations, the backward and forward times of traverse are equal, by giving special characteristics to the saw-tooth oscillation, the return traverse can be made very short compared with the actual forward time traverse, so much so that it can hardly be registered either visually or photographically. As the upper frequency limit of the saw-tooth oscillation cannot be increased as desired for reasons yet to be mentioned, sine wave time deflections are used particularly for high-frequency measuring processes. The creation of the high-frequency time oscillation is best carried out with one of the transmitting circuits used in high-frequency work. The construction of high-frequency transmitters forms an extensive subject of its own which it is not proposed to discuss within the scope of this book. Reference may be made to relevant literature for such information.[43] Only a practical hint will be given. In principle it is desirable to take the deflecting voltage from a resonant circuit. The following advantages are then obtained. Sine wave voltages can be free from harmonics; the

capacitance of the deflecting plates forms part of the oscillatory circuit; it is possible to obtain deflection voltages of high amplitude by transforming; easy adjustment of amplitude can be obtained by de-tuning the resonant circuit. With a very high amplitude which may extend beyond the edge of the screen, it is often sufficient to take only the centre portion of the sine wave oscillation which can be considered as practically linear for many measurements. In such a case, one can go further and arrange that the ray is obscured in one direction of the oscillation by means of the brightness control electrode. Of course, this is only permissible as long as the problem concerned allows the extraction of relatively short time sections.

There are many ways of producing saw-tooth oscillations of varied form. The operation of all such discharge circuits is based on the following principle. Control of the rate of time traverse and return stroke is made by increasing or decreasing the deflecting voltage the variation of which is due to the charging and discharging of a condenser. The time characteristics and magnitude of the voltage changes, as well as the frequency of the rate of discharge, are determined by type and dimensions of the auxiliary circuit components employed which take part in the charging and discharging process. The voltage rise is effected either through a resistance which results in an exponential time traverse, or by an electron tube which gives a linear traverse under conditions of current saturation. The voltage fall generally takes place through a glow discharge (spark gap, neon lamp, or thyratron) or by means of a controlled electron tube. The method of tracing the oscillogram varies according as the processes investigated are periodic or non-periodic and are of known or unknown occurrence. The latter type mostly requires a special type of coupling device for the cathode ray which will be described in detail later. Events of predictable occurrence do not usually require such a contrivance.

Whereas with non-periodic processes only a single outline of the oscillogram is made, with recurrent phenomena it is possible to trace the same oscillogram several times and so obtain greater brilliancy. In such cases, all the repeated oscillograms must have the same phase at the same point on the screen. The oscillogram of a process synchronized in this way is shown in Fig. 221. The exact synchronizing of the time frequency with the work frequency is therefore of great

importance in the tracing of periodically recurrent phenomena. Fundamentally, synchronization can be achieved in two ways. Either the size of the units used in the time base circuits, the capacitances and the resistances are selected so that their time constants result in synchronization between the rate of discharge and the work frequency, or else a special control signal is injected into the discharge circuit, and this has the same frequency as the work circuit.

With independent synchronization absolute constancy of current source and discharge circuit is essential. Its use is limited to low-frequency processes and short periods of observation. Generally, forced synchronization is based on the fact that an external oscillation is impressed on a selected part of the circuit capable of oscillating. The external impulse causes self-oscillation, within a limited range, to be produced. This phenomenon, which is known as *forced* or *induced oscillation*, appears also in saw-tooth oscillations and has been theoretically and experimentally investigated in various quarters. Leyshon,[44] for instance, couples a tuning fork electro-magnetically with a ticking circuit and develops with certain reservations a theory which refers mainly to the phase relationships in the range of synchronization. Hudec[45] discusses the forced discharge oscillations more generally whereby, in respect of phase relationships, he comes to the same conclusions, but his theory extends not only to the case where the alternating frequency and the forced discharge oscillations are equal, but where one is an even multiple or sub-multiple of the other. Synchronization by a control frequency is particularly suitable in the high-frequency range. It must be accurate enough to prevent the oscillogram wandering about in any way, since otherwise precise measurement or photographic recording of the pattern is not possible. For the same reason, the oscillogram must not move rapidly round a zero position and such movement as occurs during imperfect synchronization is a

FIG. 221. SYNCHRONIZED OSCILLOGRAM OF A DISTORTED SINE WAVE OSCILLATION

direct measure of the completeness or otherwise of the synchronization. With a good discharge tube, the range of variation is about 1–½ per cent, and is determined largely by the stability of the discharge in the tube and depends on the special construction of the glow lamp. For thyratrons the range of deviation is up to 0·05 per cent, and for electron tubes it is of the same magnitude. Errors of synchronization and deviation of the pattern must be made as small as possible if large differences in frequency are to be dealt with under stable conditions. With glow lamps a frequency ratio between work and time circuits of less than 1 : 10 can only be attained with difficulty in one stage. With thyratrons or discharge valve circuits, frequency ratios up to 1 : 50 can be secured if the current sources possess the necessary high degree of stability. If one desires to go further and trace other periodic curves which have still greater frequency ratios, then it will be necessary for the control voltage first to synchronize a time base unit in the way described and thus in turn to control a second circuit in the same way. In order that the voltage may never fail to rise to the discharge point and the forced oscillations never get outside the range over which the control frequency can pull them into step, the voltage amplitude of the control frequency must be constant.

As the above remarks show, adjustment of all the variables is a relatively easy, and therefore an outstanding feature of electrical time deflection: frequency, time velocity, and length of the time base can be varied by the appropriate adjustment of the circuit components. The position of the oscillogram relative to the surface of the screen can also be adjusted easily by suitable selection of bias potential at the time plates. It is particularly significant that by using suitable discharge circuits, tracing velocities up to 100 000 km. per sec. can be attained for time deflection. Such high tracing speeds cannot be used, of course, with low-voltage tubes when a single trace is involved. In modern tubes, the maximum tracing speed for visual observation is about 1 000 km. per sec. Before the fundamental principles of electrical time deflection circuits are examined in more detail, reference may be made to a process developed by Bab [46] in which optical time deflection with rotating mirrors and electrical time deflection are employed simultaneously (Fig. 222). This method permits of the use of two different frequencies which can be inharmonic to each

other. The high-frequency process is converted stroboscopically into a low-frequency process which, in turn, is split up by a rotating mirror. If the process to be investigated has a frequency which is nearly equal to the sinusoidal frequency of the time base in the abscissae, the resultant Lissajou figure creeps over the surface of the screen, at a velocity corresponding to the difference in frequencies and traces a rectangle of uneven

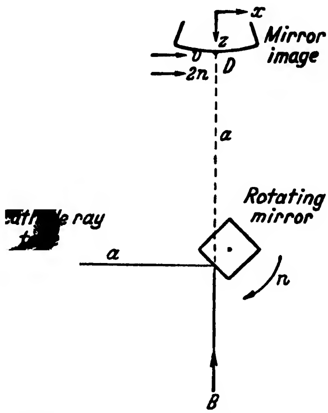


FIG. 222. COMBINATION OF DEFLECTION BY A ROTATING MIRROR AND ELECTRICAL TIME DEFLECTION

brilliancy. A translational velocity v is superimposed on the wandering velocity of the Lissajou figure owing to a movement of the cathode-ray tube or the insertion of a rotating mirror. For

$$v = 2\pi A(f_1 - f_2) \quad . \quad . \quad . \quad (49)$$

where f_2 is the work frequency and f_1 the frequency of the electrical time deflection, the curve $y = F(f_2 A)$ stands out distinctly and true to type in Cartesian co-ordinates from the hazy lines parallel to the x-axis. The magnitude of the velocity v depends on the number of revolutions, the number of surfaces and the distance between the rotating mirror and the cathode ray tube, all of which must be adjusted to the frequencies to be investigated.

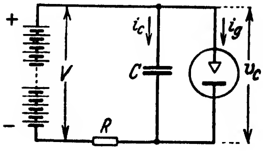


FIG. 223. FLASHING CIRCUIT

(B) SAW-TOOTH DISCHARGE CIRCUITS WITH GLOW LAMPS AND THYRATRONS. Low-frequency discharges with triangular or

saw-toothed characteristics can be most simply produced by ticking circuits using a neon lamp with linear or exponential voltage rise and discharging with a very rapid fall of potential across its terminals. With the assistance of a simple ticking circuit, without forced synchronization (Fig. 223) consisting of glow lamp, condenser, resistance and charging battery, let us trace qualitatively first of all the processes involved in the familiar arrangement of glow lamp with condenser and resistance from the static characteristic. From the outset it must be understood that the following considerations omit the inertia of the lamp, hysteresis phenomena, and self-inductance.

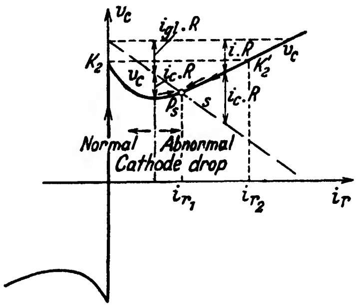


FIG. 224. STATIC CHARACTERISTIC OF A NEON LAMP

Fig. 224 shows in v_c the static characteristic of a neon lamp with electrodes of the same size.[47] We will consider firstly the stable condition and what happens on switching on. If first of all it is assumed that the lamp is connected to the voltage V ($R = 0$ in Fig. 223), the current, i_{gl} in the circuit, corresponds to the battery connexion P_s in Fig. 224. The condenser in parallel with the lamp does not influence the stability of the arrangement in any way. Suppose a positive resistance R is now introduced into the circuit and assume that the point of intersection of the corresponding resistance line

$$r\,[(V - i_{gl}R)i_{gl}] \quad . \quad . \quad . \quad (50)$$

with the characteristic v_c is P_s. It will be agreed that this condition, like the first one, is stable, i.e. the lamp still functions with reduced current. The difference between the lamp or condenser voltage v_c and the applied voltage V must be absorbed in the resistance R should the equilibrium be upset, whence

$$V = v_c + iR = v_c + i_{gl}R + i_cR.$$

$$\therefore \quad i_c = C(dv/dt)$$

$$= (V - i_{gl}R - v_c)\,(1/R) = (r - v_c)\,1/R \quad . \quad (51)$$

i.e. the right-hand side shows that for each abscissa the charging current of the condenser is proportional to the

distance of the lamp characteristic v_c from the resistance line r. Assuming that the equilibrium is disturbed at a given moment and that i_{gl} is slightly smaller than the value corresponding to the operating point P_s, then this difference becomes positive, i.e. $i_c = C \cdot (dv/dt) > 0$; the lamp voltage v_c must in fact increase with time until equilibrium at P_s again is established. In this way the operating point on the lamp characteristic tends to move away from the position of disturbed equilibrium. It follows immediately that this direction of movement in Fig. 224 is towards the equilibrium position P_s, i.e. the equilibrium position is stable. The question now arises what happens when the lamp is switched on and how can the stable operating point be reached? At first, the lamp represents an infinite resistance, i.e. the condenser C charges up in the well-known way exponentially with time through the resistance R, during which process the operating point of the lamp moves on the ordinate axis from O to K_2. As soon as this point K_2, i.e. the striking voltage, is reached, v_c cannot increase further, although $i_c \cdot R = R \cdot C \cdot (dv/dt)$ being still positive, it demands that v_c should increase. In consequence, the operating point jumps over on the rising branch of the characteristic to K_2 at which, ignoring the self-capacitance, the lamp current rises in surges to the value of i_{gl2} and then finally takes up the position P_s. Therefore, the lamp even when connected through resistances at first glows brightly for a short time, and then continues to glow at reduced brilliancy. From consideration of the stable condition and the method of connexion, we now come to the condition which results in the periodic discharge. R is now increased until, according to Fig. 225, the equilibrium position lies between K_1 and K_2 on the lamp characteristic. Following the considerations on the subject of stability, the directional arrows inserted show that the point P_2 must be unstable. Switching on results as follows. v_c again rises to K_2, jumps over to K_2' and falls to K_1 at the prescribed rate. Here the distance between the characteristic and the resistance line requires a further drop from v_c, but the characteristic only permits of this after immediate transfer to K_1', i.e. the lamp is extinguished, the voltage rises again to K_2 and the cycle commences afresh. Fig. 225 (b) shows qualitatively the procedure repeated periodically showing the current and voltage to a time scale. Sources of quantitative error were referred to at the start.

The striking and extinction potentials, and also the spread of the ranges of normal and abnormal cathode drop, are dependent to a great extent on the material of the cathode and its shape, as well as the gas used for filling the tube. The value of the voltage, of the resistance R, and capacitance C shown in Fig. 223, determines the shape and time traverse of the saw-tooth oscillations. The time constant resulting from the

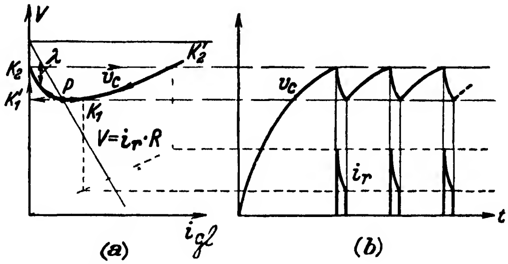


FIG. 225. CHARACTERISTIC OF A NEON LAMP IN A FLASHING CIRCUIT WITH APPROPRIATE TIME SCALE

charging resistance R, and capacitance C, determines the period of rising voltage and that due to C and the lamp resistance determines the fall. The rise corresponds to the time base of the oscillogram to be traced; the fall brings about the fly-back of the cathode ray to its initial position. As the return time should be as small as possible compared with the forward time traverse, the magnitudes of the components in the discharge circuit must be selected to secure this condition. If the time of fly-back is to be as short as possible, the capacitance must be reduced to a minimum, the irreducible limit being the self-capacitances which are of the order of 5 $\mu\mu$F. With a glow lamp circuit of this kind it is possible to attain frequencies up to 100 000 cyc. with ticking circuits if one is prepared to accept the resultant reduction in amplitude which occurs as the discharge frequency is increased or alternatively to arrange for subsequent amplification. To reduce the time lag of the discharge, the tube is filled with hydrogen for high frequencies. Charging capacitances of the order of 10 $\mu\mu$F. are only used for high frequencies where

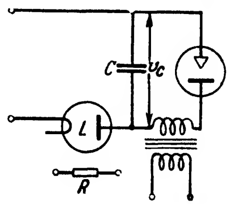


FIG. 226
FLASHING CIRCUIT WITH CONTROL TRANSFORMER AND NEON LAMP

the curve must be traced without interruption, as the poor result which is necessarily obtained is a definite disadvantage.

Fig. 226 shows a ticking circuit which is a development of the circuit shown in Fig. 223 with the addition of a transformer for synchronization. In order to ensure constancy of the voltage gradient dv/dt, even with a large difference between the striking and extinction voltages, a valve has been substituted for the resistance R. If the circuit is operated under conditions of current saturation in this valve, a linear instead of an exponential rise of voltage with time will be obtained, and this makes the evaluation of the oscillogram easier. The passage of current by adjusting the filament heating is easier, and can be carried out over wide limits. It should be noted that the direct voltage used is high compared with the striking voltage of the lamp, so that the tube can operate with safety under conditions of current saturation. An advantage of this circuit is that the source of synchronizing voltage, except at the moment of discharge, in the ticking circuit, is generally unloaded, and there is no disturbance of voltage rise in the ticking circuit from this cause. A disadvantage of this old circuit, which is now seldom used, is that the discharge process is slowed down and reacts strongly on the primary side of the synchronizing transformer or coupling link provided in its place. In order to manage with small resistances in the discharge circuit, and to eliminate reaction which becomes particularly objectionable if the measured voltage is to be used simultaneously for synchronization, the synchronizing voltage is generally fed through one or more amplifying stages. This circuit, therefore, involves considerable equipment. Fig. 227 shows oscillograms of the discharge process in the lamp and the way in which this is affected by a resistance in the discharge circuit. The upper is the current curve with

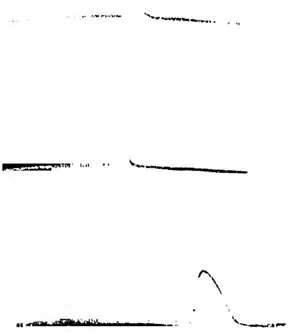


FIG. 227. CURVES SHOWING CURRENT IN A TIME DISCHARGE CIRCUIT HAVING VARIABLE RESISTANCE

Length of oscillogram - $\frac{1}{80}$ sec.
$C = 10^3$ $\mu\mu$F. Approx.

a non-inductive series resistance of about 5 000 ohms. The centre oscillogram represents the conditions without resistance or inductance. The lower one shows the slurring effect of the resistance and inductance of the synchronizing transformer. On the one hand, the last oscillogram shows the slurring effect of the inductance which produces an oscillation, and on the other hand it will be seen how the ohmic or inductive resistance increases the fly-back time of the discharge circuit. Whereas the discharge time is about $0{\cdot}5 \,.\, 10^{-4}$ sec. in a circuit without resistance, i.e. through the internal

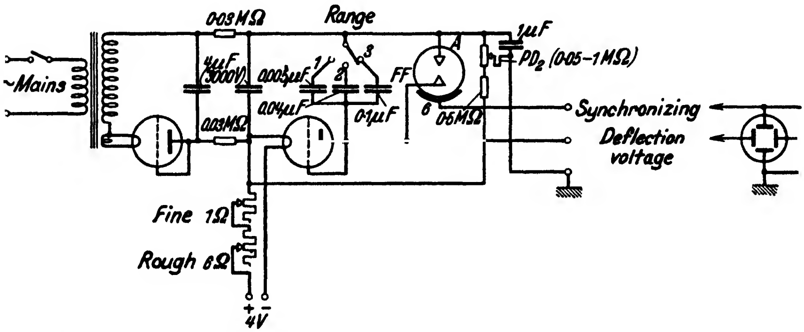


FIG. 228. SIMPLE NEON LAMP CIRCUIT WITH EXTERNAL CONTROL OF SYNCHRONIZATION FOR PRODUCING SAW-TOOTH OSCILLATIONS

resistance of the lamp alone, this period is increased about five times by the synchronizing transformer.

In order to dispense with the control transformer, it is expedient to attain synchronism by means of a special control inside or outside the discharge tube, this control directly influencing the discharge in the tube itself. The first case leads to the use of the grid-controlled discharge tubes, known as *thyratrons*; the latter case is exemplified by the externally controlled discharge tube. Fig. 228 shows a discharge circuit in which a lamp is controlled by an external electrode. Direct current is obtained from an a.c. supply through a hot cathode rectifier, the output being well smoothed to avoid introducing undesirable disturbances. The condenser is charged at a uniform rate by the saturation current of another valve. The discharge condenser is divided so that sufficient variation in time velocity can be obtained. The position of the oscillogram on the screen is adjusted by variation of

the bias voltage through potentiometer tappings. Although the a.c. heating of the rectifying valve is carried out from a winding of the mains transformer, the charging valve is heated from a separate accumulator. Heating from the mains should

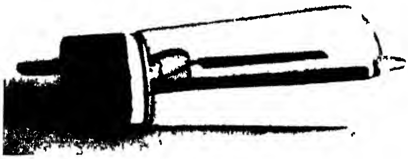


FIG. 229. NEON DISCHARGE LAMP WITH EXTERNAL CONTROL ELECTRODE (*Leybold's A.G.*)

be avoided in principle in this case, because mains voltage variation causes considerable changes in emission. Perfect synchronization could not be obtained, and the splitting up of the figure would naturally result. The discharge is effected

FIG. 230. INTERIOR OF A TIME BASE CIRCUIT SYNCHRONIZED BY AN EXTERNAL CONTROL ELECTRODE

by the external electrode which is connected to the synchronizing voltage. The metallic coating which comprises this electrode is sprayed on the glass bulb shown in Fig. 229. With such externally controlled tubes, as in fact with any sealed off discharge lamps, the striking and extinction voltages are

practically constant so that the limits of the discharge, in such a tube, are known. If a larger or smaller voltage amplitude is desired, the tube must be changed for one of a different rating. The externally-controlled discharge tube operates with a synchronizing voltage as low as 20–30, so that, in most cases, the measured voltage can be used for this purpose. The interior view of such an equipment with external control of synchronization is shown in Fig. 230.

Fig. 231 shows a standing figure obtained with the circuit

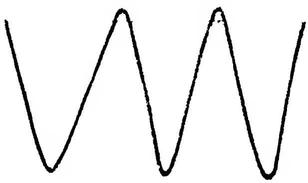


FIG. 231. FIGURE SYNCHRONIZED BY EXTERNAL CONTROL (SINUSOIDAL VOLTAGE 800 V.)

of Fig. 228, and indicates clearly the short fly-back period. One particular advantage which this method of synchronization has over the older arrangement is the absence of reaction and the extremely simple connexions. The connecting up of the external electrode, which has a capacitance of less than 10 $\mu\mu$F., does not put any appreciable load on the measured voltage. If the charging valve is to have its heater operated from the mains, it is preferable to use an indirectly heated screen-grid valve. With the screen-grid valve, the current charging the condenser is independent of the voltage on the condenser, on account of its high amplification factor. It is advisable for constancy of current and voltage to introduce glow discharge tubes as stabilizers. Even without such additions, the charging currents in mains-operated equipment are constant enough to prevent synchronization being upset. An example given in Fig. 232 is one of a rather old saw-tooth oscillation circuit with a screen-grid valve developed for television. This principle of charging can be used, of course, not only for the glow lamp synchronization arrangement as shown, but also for any other discharge and synchronizing circuits (e.g. glow lamp with

external control, thyratron circuits, mechanical contacts, etc.). A disadvantage of this arrangement is that the charging current, and therefore the resulting discharge frequency, can only be adjusted by variation of the grid bias over a comparatively narrow range. Consequently, if wide frequency ranges are to be covered, the capacitances must be variable over a considerable range when charging through a screen-grid valve. The

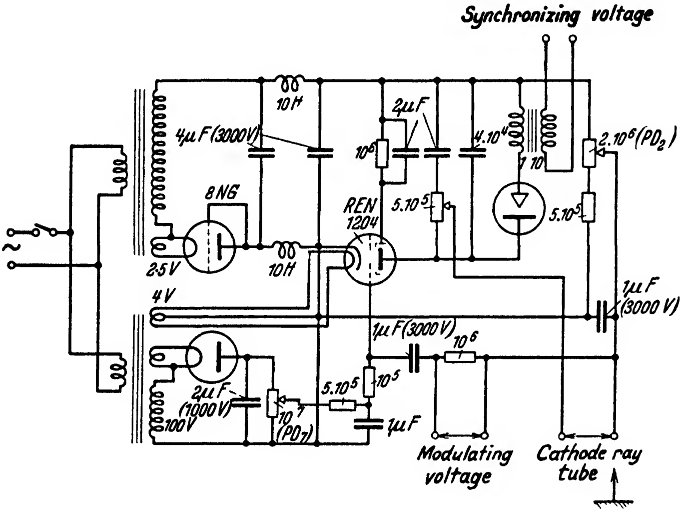


FIG. 232. TIME BASE CIRCUIT WHICH ADMITS OF MODULATION, THE CONDENSER BEING CHARGED THROUGH A SCREEN GRID VALVE

screen-grid valve has a property which gives it a great advantage over other alternatives for use in a saturated current charging circuit. It is capable of altering the charging currents without any lag. To do this it is only necessary to feed alternating voltage to the grid of the valve. If the frequencies of the modulating alternating voltage are high compared with the discharge or saw-tooth frequency, the slope of the rising portion of the discharge curve is modulated in steps. If the modulation frequency is small compared with the discharge frequency, then the duration of the individual discharges will vary. The possibility of effecting modulation in this way is of considerable importance in special television problems as well as for special problems involving measurement. Following on the discussion concerning a method of modulating the charging

current, let us discuss briefly what are the limits within which this current varies in practice. It was stated above that the discharge current is limited by the properties of the lamp. With commercial lamps it is of the order of a fraction of an ampere. In the case of well-shaped discharge curves, where the charging time is long compared with the time of discharge, the currents may be a few milliamperes at the most. On the other hand the current cannot be reduced as desired. For instance, in producing very slow saw-tooth oscillations it is not feasible

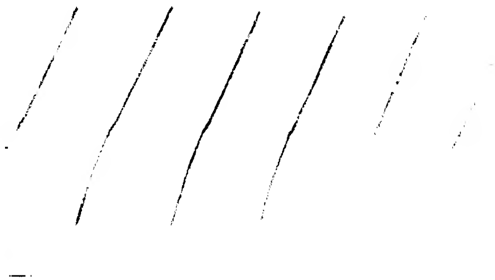


FIG. 233. TIME DISCHARGE CURVE IN WHICH THE RISING PORTION IS SLIGHTLY DISTORTED (CHARGING CURRENT AND CAPACITY ARE TOO LOW)

to reduce the rate of discharge by merely decreasing the charging current. In the older type of tube construction particularly, doing this brings the charging current to the same order of magnitude as the current to the deflecting plates, when distortion of the discharge curve will occur and external origin error will become relatively large (see above).

Fig. 233 shows an oscillogram for a saw-tooth oscillation circuit taken under these conditions from which the zero error is clearly visible. In order, therefore, to obtain linear time deflections of slow traverse, the charging capacitance must be increased. Also, the limits indicated above must also be taken into account here, for an increase in the charging capacitance in certain cases causes such an increase in the discharge current that the area in which the lamp operates is displaced into the range of the abnormal cathode drop, leading to disturbances in the discharge process. Consequently, for slow time deflection, lamps with large electrode area which will

with certainty remain in the area of the normal cathode drop, should be used where possible. In the production of higher frequencies also, large capacitances and lamps with large area electrodes should be used in cases where the discharge circuit is heavily loaded.

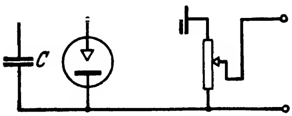


FIG. 234. VOLTAGE DIVIDER FOR A TIME DISCHARGE CIRCUIT

As already stated above, it is hardly possible with glow lamps to vary the amplitude of the discharge voltage by simple external control. Nevertheless, the possibility of such amplitude adjustment will be desirable in many cases. Subsequent regulation of the amplitude can be obtained by a voltage divider a suitable arrangement of which is shown in Fig. 234. In order to avoid distortion of the current characteristic, such a discharge voltage divider must operate independently of frequency over an extremely wide range up to about fifty times the discharge frequency to ensure that there is no rounding-off of the upper and lower peaks of the discharge curve. To meet this condition, in spite of unavoidable parallel capacitances, the non-inductive voltage divider must not be too highly rated. When such a divider is used, therefore, a high load on the discharge circuit must be anticipated, and this should be obtained through a subsequently coupled valve and not through the circuit of Fig. 234. The capacitance coupling provided in Fig. 234 must be chosen so that the lowest fundamental frequency is transferred without difficulty or phase displacement. Distortion of the discharge curve is only effectively avoided when the reactance of the coupling

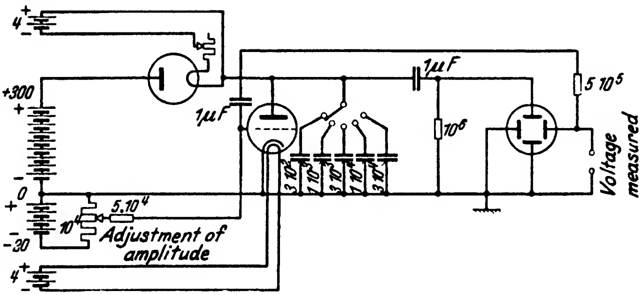


FIG. 235. TIME BASE CIRCUIT FOR BATTERY OPERATION USING A THYRATRON

condenser for a sine wave voltage of the discharge frequency amounts to one-tenth the ohmic resistance of the divider. Such a voltage divider is particularly useful when the discharge voltage is to be amplified. Its application, however, is usually limited to the range of lower frequencies. If voltage division, independent of frequency over a wide range is desired, capacitance dividers similar to those previously described may be used.

When using an amplifying stage in the time-base circuit the anode resistance feeding the deflection voltage to the plates can conveniently consist of a potentiometer to permit simple adjustment of the amplitude without reaction on the discharge circuit. A simpler and less distorted regulation of the discharge voltage amplitude can be carried out by thyratrons. The range of regulation with these units is sufficient for most purposes. The thyratron is a hot cathode gas-discharge tube in which the discharge is controlled by an electrode mounted between cathode and anode. The physical properties of the grid control of gas-discharge tubes have already been discussed at length elsewhere.[48] The circuit arrangement of a simple battery-operated discharge circuit using a thyratron is shown in Fig. 235. This only differs from the earlier discharge circuits in that the grid circuit of the tube appears as an addition. By making the initial voltage of the control grid more or less negative by means of the potentiometer shown, the striking voltage can be adjusted and variation of the discharge amplitude obtained. A resistance is connected in the grid circuit—this must not be of too high a value on account of the high grid current—in order to superimpose on the direct voltage of the control electrode an alternating voltage for the purpose of synchronization as discussed in more detail below. It follows naturally that when the discharge amplitude in the circuit of Fig. 235 is adjusted, a change in the discharge rate takes place since the charging current remains constant.

For certain applications, such as tracing sound-film amplitude curves, it may be of interest to modulate the amplitude at constant frequency. Fig. 236 shows a circuit devised by the author which is suitable for this purpose. In this, the modulating voltage is applied also to the grid of the screen-grid charging valve with the same phase but variable amplitude. In this way, the condition that the charging current increases immediately the discharge amplitude increases, is secured.

With this contrivance it is possible to control the amplitude of the discharge without simultaneous frequency modulation.

It is usual, in practice, to communicate an alternating voltage to the grid of the control valve also by transformers instead of condensers. In choosing the coupling unit the fact that the internal grid resistance of the discharge tube may at times be low, should not be forgotten. If the a.c. frequency at the control grid of the gas-discharge tube is equal to or lower

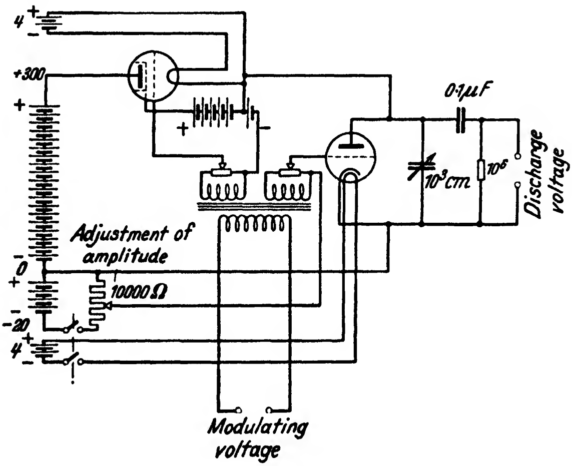


FIG. 236. CIRCUIT FOR MODULATING THE AMPLITUDE OF THE DISCHARGE WITHOUT MODULATING THE FREQUENCY

than the frequency of discharge, extremely stable synchronization of the discharge circuit can be obtained. One particular advantage of the hot cathode discharge tube is noticed here, viz. that the striking and extinction voltages show very great constancy. The regularity of operation with good thyratrons approximates in discharge circuits to that obtained with high-vacuum valves. Another distinction from glow lamps, due to the more satisfactory ionization from the hot cathode emission, is that the thyratron even in combination with capacitances of several hundred micromicrofarads can be used for high frequency. For instance, with the circuit of Fig. 235 and the A.E.G. valve T166, rates of discharge up to 100 000 cyc. could be produced although with only relatively low amplitudes of about 20–30 volts.

Fig. 237 shows a circuit using a thyratron and charging

through a screen-grid valve for all-mains operation, which permits of simultaneous adjustment of the stationary position of the ray in both co-ordinates by bias voltage. The presence of a non-inductive resistance of several hundred ohms in the anode circuit of the gas-discharge tube is worthy of note. This resistance serves to limit the current and protect the gas-discharge tube from serious overload, and its use is particularly recommended when large charging condensers are

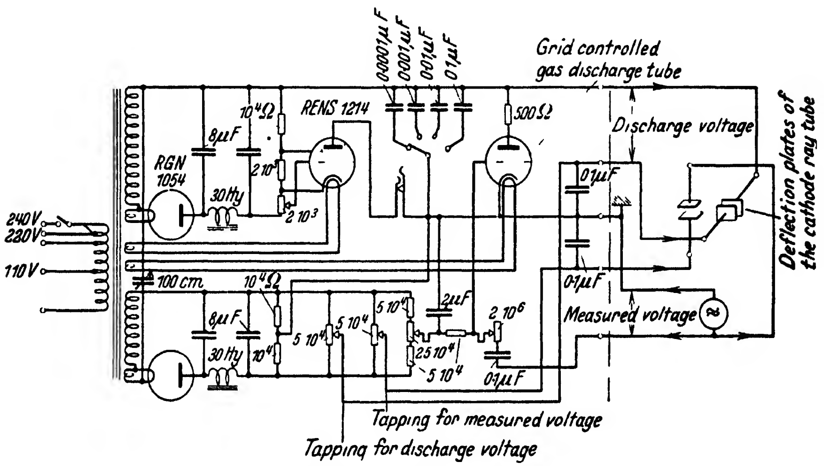


FIG. 237. AN OLD FORM OF TIME BASE CIRCUIT INCORPORATING A THYRATRON FOR MAINS OPERATION

employed. In contrast to high-vacuum tubes with indirectly-heated cathodes, a potential difference of more than 10 volts must not exist between cathode and heater of a thyratron. As an example, it was for this reason that in the circuit of Fig. 235 separate heating batteries for the charging valve and discharge tube were used. The heating of the gas-discharge tube in Fig. 237 is carried out by means of a separate transformer winding for the same reason.

Synchronization of the rate of discharge, which with these discharge tubes permits of a frequency division of 1 : 50, takes place at the control grid by means of an alternating voltage of about 1 volt. The necessary control voltage is therefore considerably less than in the case of glow lamps where, for instance, in externally controlled synchronization, the minimum r.m.s. value must be 20 volts. Nevertheless, the power consumption

with the thyratron must not always be overlooked, since the voltage mentioned must be maintained across a resistance of about $5 \cdot 10^4$ ohms. In the discharge circuits previously discussed a good performance can be obtained by keeping the charging current of the condenser constant. This method is expedient if the voltage of the condenser is to be used directly for deflection, and therefore it is required that the discharge voltage amplitude shall be as great a proportion of the voltage of the source charging the condenser as possible. Besides this method, there is another and simpler way of obtaining a good curve. This second method is mostly adopted in time-deflection equipment for measuring purposes, as well as for discharge circuits for television equipment. It consists in selecting the discharge tube or adjusting it so that the difference between the striking and extinction voltages is small compared with the voltage of the charging source. Then the voltage range which is taken from the charging curve of the resistance-condenser unit is so small that it is generally linear in practice. But to obtain sufficiently large discharge amplitudes, an amplifying stage is necessary. With a given difference in striking and extinction voltages, the frequency of the resulting discharge depends on the value of the capacitance C and on the charging current; or with a constant current source, on the magnitude of the charging resistance. As in operation with mains equipment, voltage fluctuations must be taken into consideration, the locking synchronization must always be made strong enough, so that no alteration to the discharge frequency takes place in spite of the fluctuating charging current.

Much better conditions of operation are secured when the voltages in the mains section of the discharge circuit are kept constant by neon stabilizers. The stabilization of all voltages in the discharge equipment is not practicable economically on account of the high current consumption, and high direct voltages generally present. If stabilization is required, it is sufficient, in order to keep the discharge rate constant, to keep the charging voltages constant at several hundred volts on the one hand and the grid voltage of the thyratron constant on the other. As only feeble currents are required for charging as well as for the grid bias of the thyratron, it is sufficient to use neon stage dividers for the stabilization of such small currents. The circuit of an equipment for measuring purposes with capacitances charged through a resistance, stabilized

charging with thyratron grid bias and subsequent amplification is shown in Fig. 238. In the process discussed—keeping the difference between the striking and extinction voltage as low as possible compared with the voltage of the current source—it becomes necessary to amplify the discharge voltage by connexion of an additional stage. This form of discharge circuit is advantageous for a number of reasons besides the fact that small demands are made on the discharge tube, especially if a thyratron. The addition of an amplifying stage enables a deflection voltage which is symmetrical to earth to be obtainable with comparative ease. The connexions of such a stage are exactly the same as those shown in the circuit of Fig. 186, already discussed. If the mains equipment supplies a direct voltage of 800, undistorted discharge voltages up to 1 000 volts can be obtained with the circuit of Fig. 238. This voltage is sufficient to modulate even the large screen of high-vacuum tubes operating at 4 000 anode voltage. If the tube R_4 is a thyratron of the usual construction, discharge frequencies up to about 20 000 cyc. can be obtained. In the grid circuit of the thyratron is a voltage divider for synchronization, which permits the adjustment of the voltage necessary for positive operation. Such a voltage divider is necessary to ensure against too strong a lock in synchronism, which always results in distortion or disturbance of the shape of the discharge curve.

Regulation of the amplitude of discharge is here again carried out by the usual bias voltage adjustment. With this regulation there is, of course, co-ordination of amplitude and frequency mentioned above. Because of this, the regulation has the advantage that with smaller amplitudes, the subsequent amplifier is seldom fully loaded, and therefore has a particularly low distortion.

(c) Saw-tooth Discharge Circuits Using Hard Valves. The discharge circuits discussed in the last section, especially those devices with thyratrons, are relatively simple arrangements which suffice for the treatment of most problems. The stability of the various arrangements discussed is so great that it satisfies even the high demands which are made in the synthesis of high-definition television pictures. Although discharge circuits using hard valves, as distinct from the others discussed, have not as yet proved adequate for measuring purposes, it is intended to discuss them in detail here. Such circuits using valves have a definite sphere of application: precise periodic

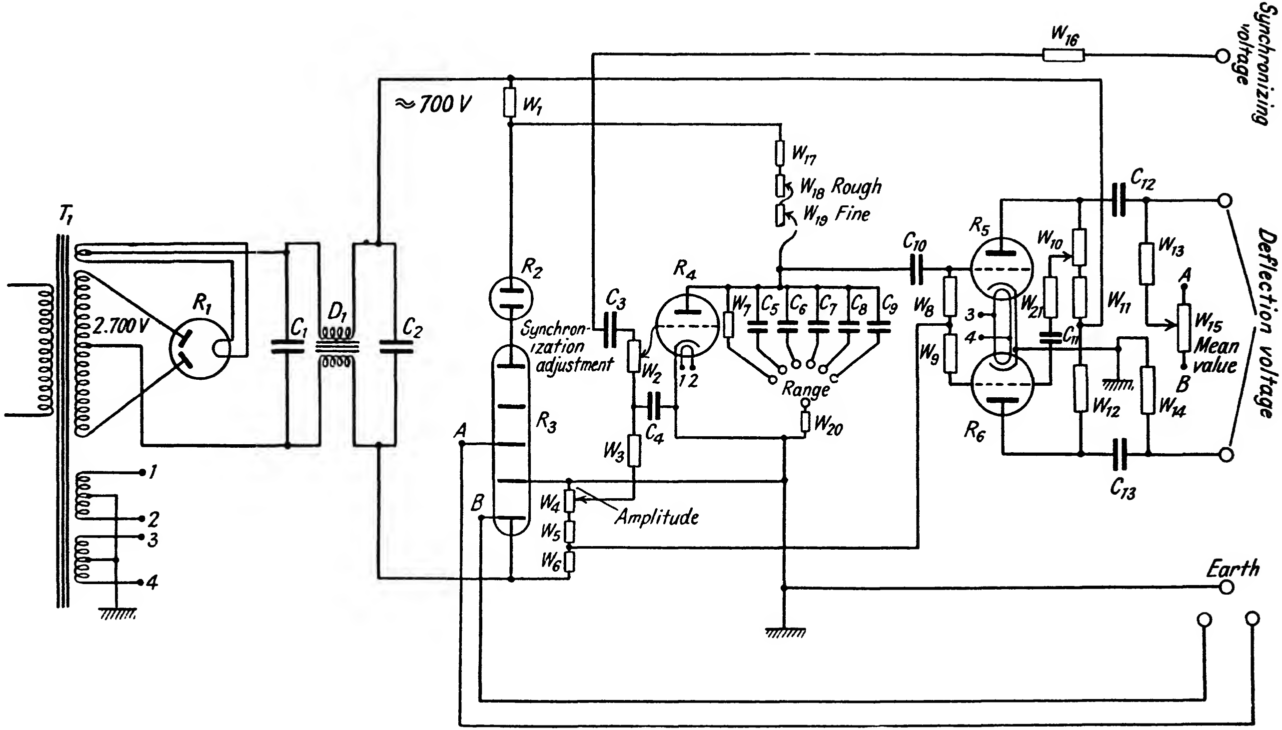


FIG. 238. CIRCUIT OF A PUSH-PULL THYRATRON EQUIPMENT FOR MEASURING PURPOSES

time deflection at very high velocity. The gas-discharge valves, hitherto discussed, fail as has been shown many times before, as soon as medium or high-frequency pulses are required. It appears also that constancy of characteristics which must be obtained in order to get good standing figures at high frequencies, cannot be achieved with gas-discharge tubes. With the same limiting conditions, therefore, a high-vacuum tube circuit instead of a gas-discharge unit, should be used in investigations which involve high-frequency time deflection. From the standpoint of circuit classification, the extremely numerous and at first sight very varied pulsating circuits using valves, can be grouped under two principal headings: the dependent and the independent remote control. The dependent and entirely remotely controlled pulsations exist only as long as a controlling voltage is present, and they follow this in synchronism with the greatest precision. Independent pulsating circuits are those which are free to operate even in the absence of a remote control alternating voltage. All circuits which work in this way prove on closer examination to be nothing other than modified valve oscillator circuits. The conditions required for the production of free pulsations are identical with those for self-excitation; a falling characteristic is necessary. The excited oscillatory circuit must in addition be abnormal, i.e. one of the two energy feeders L and C of the oscillatory circuit must outweigh the other. Which of the two predominates depends on the type and circuit arrangement of the saw-tooth oscillation device employed.

So far we see the following circuits for the production of free saw-tooth oscillations in the analogy with the valve oscillator—

Space charge circuit.
Electron circuit.
Reaction coupled circuit.

All these free pulsating arrangements can be synchronized by a remote alternating voltage which has the same frequency or a sub-multiple of it. At the same time the alternating voltage produces amplitude conditions for discharging at an instant which is near its own maximum in time. It becomes effective in performing its desired function only when it is increased to the peak value of the discharge voltage by the superposed free pulsation voltage. The explanation of the frequency

reduction is as follows. The control voltage imposes a maximum value on the saw-tooth oscillation at the precise instant of flashing, independently of the preceding low-amplitude impulses.

Unfortunately with many independent valve discharge circuits, the curve shape which results is not sufficiently linear for the purposes of oscillography. For this reason valve circuits of the second type—the dependent remotely controlled—which are far better in form of curve than the first, are to be preferred. The same principles which underly the dependent remotely controlled discharge circuits can be traced in Fig. 239. Two

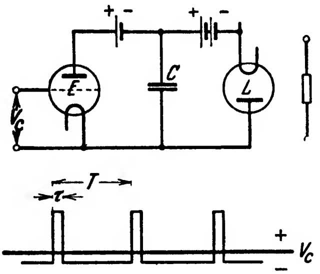


FIG. 239. TYPICAL REMOTELY CONTROLLED TIME BASE USING VALVES

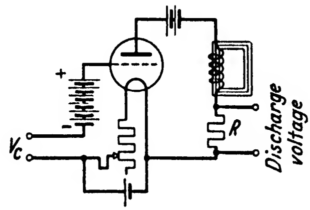


FIG. 240. DYNATRON AS A MEANS OF PRODUCING TIME DISCHARGES

valves, L and E, of which the charging valve L can be replaced by a resistance R, are connected to a condenser C. The current in E is restrained by a bias potential and is in direct external connexion to a control voltage V_c. The control voltage must have the rectangular time traverse indicated. The return period must be short in comparison with the whole cycle. The difference between the familiar discharge circuits lies in the production of this distorted control voltage from the external source. Usually one valve, or perhaps sometimes two, are used for this purpose. The circuit arrangements become very complicated, but they give the best results. A few typical valve circuits of both main groups are shown. A typical independent circuit arrangement uses the dynatron. By reducing considerably the capacitance in the oscillatory circuit the familiar dynatron circuit is converted into the valve-controlled discharge circuit of Fig. 240. The shape of the discharge curve is not by any means good enough for the demands likely to be made upon

it. With low frequencies an improvement can be made by using a closed iron cored inductance, i.e. by employing the inductance drop. The saw-tooth voltage circuit allows pulse potentials to be taken from *R* to the deflecting plates of the cathode-ray tube. Fig. 241 shows a circuit in which a valve with saturated current is connected in parallel with the dynatron. The saturation current is adjusted to equal the maximum negative current of the dynatron which enables a satisfactory pulse curve to be obtained.

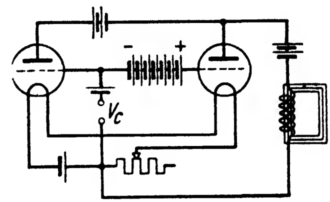


FIG. 241. IMPROVING THE SHAPE OF THE DYNATRON CURVE BY PARALLEL CONSTANT CURRENT

The disadvantage of both arrangements is that the controlling alternating voltage V_c is subjected to considerable load, due to emission from the dynatron grid. In addition, very large valves are necessary for high-frequency oscillations, and in consequence high losses have to be taken into account (transmitting valves).

With suitable bias voltages and parallel connexion of both grids of a double-grid valve, a falling characteristic in the grid and anode circuits can be obtained. Fig. 242 shows how both grids are electrically coupled through a common resistance lead *R*, whence the space charge grid receives about half the saturation current through the battery circuit shown, whereas the normal grid in practice receives only a small current on account of its bias. This circuit appears again as an oscillating audion (Roosenstein's Negadyn) in radio reception, *R* being replaced by an oscillatory circuit. If the grids are subject to voltage variation, this circuit behaves like a direct coupled amplifier which increases in sensitivity as *R* increases, but becomes unstable at a critical value of *R*. The arrangement is then equivalent to a kind of pulsating relay, i.e. a system which can only assume two stable conditions: between maximum and zero anode current the system pulsates backward and forward without inertia if the grid or anode circuit is suitably excited. In the circuit of Fig. 242 saw-tooth oscillations occur

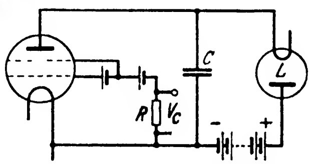


FIG. 242. FOUR-ELECTRODE VALVE AS A RELAY FOR PRODUCING TIME DISCHARGES

through the introduction of the capacitance C, which is charged at a uniform rate by the charging valve L. The pulsations can again be controlled by voltages across R. Ignoring a rounding off at the discharge point, the curve has a useful form, but the load on the controlling source is again fairly high.

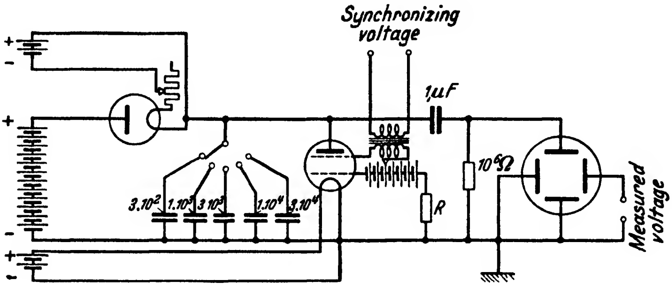


FIG. 243. SIMPLE VALVE CIRCUIT FOR PRODUCING TIME DISCHARGES FOR MEASURING PURPOSES

An arrangement somewhat more favourable in this connexion is given in the diagram, Fig. 243, which shows a complete arrangement for measuring purposes. On account of its great simplicity, this circuit has attained considerable importance among valve-controlled saw-tooth oscillation circuits, especially for television.

A dynatron circuit with screen-grid valve capable of producing pulsations, whose method of operation results from the special characteristics of the screen-grid valve, has been published by Ulbricht.[49] The grid of the valve, as shown in Fig. 244, is connected to a tapping on the resistance R_a in the anode circuit, so that the grid voltage varies with the anode current and a deflection of the cathode ray proportional to time is obtained. The shape of the pulsating curve depends greatly on the outline of the valve characteristic. The pulsating circuit is synchronized by superimposing a controlling alternating voltage on the grid circuit in such a way that it just exceeds the unstable portion of the characteristic. In the very short

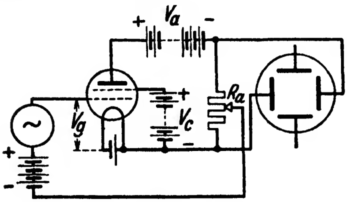


FIG. 244. TIME BASE CIRCUIT USING A SCREEN-GRID VALVE (*Ulbricht*)

time involved in the flashing process, frequencies of 10^7 cyc. can still be observed quite comfortably. Developments have shown that such a circuit arrangement as the dynatron or negadyn, which operate under abnormal current conditions in electron tubes, are generally replaced by circuits which include hard valves operating under normal conditions. A two-valve circuit familiar since 1920 forms the basis of the important group of reaction coupled circuits: the *Kallirotron* of Turner. Fig. 245 shows the connexions of this circuit which is identical with a direct-coupled amplifier. The second valve is chiefly used for phase reversal. With a suitable degree of amplification or magnitude of the coupling resistance, this system also becomes unstable, and as soon as the input voltage exceeds a peak value operating in the correct sense it adjusts itself to one of its unstable limiting conditions in which the anode current of either valve I or II is cut off.

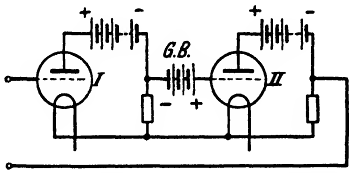


FIG. 245. KALLIROTRON (*Turner*)

This circuit again forms a pulsating relay and is now of the greatest importance even in other spheres of electro-technical

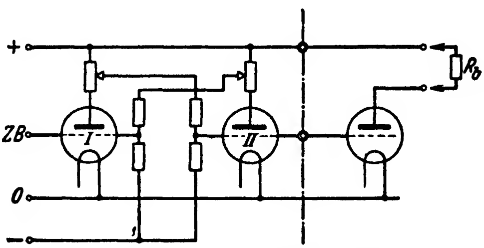


FIG. 246. KALLIROTRON WITH CENTRAL BATTERY OPERATION

research, for instance in research on transients. Fig. 246 shows the Kallirotron in a practical circuit; the separate batteries are replaced by one common battery, and the third valve is for controlling the circuit.

The system is enabled to produce saw-tooth oscillations only after the introduction of a condenser. The ordinary resistance amplifier with only one coupling circuit in place of the grid battery *G.B.* (Fig. 245) gives rise to saw-tooth oscillations as soon as reaction is introduced between anode II and grid I.

The best-known form of construction of a reaction coupled two-stage amplifier is the *multivibrator* of Abraham and Bloch,[50] shown in Fig. 247. One can recognize the reaction coupled resistance amplifier whose pulsation frequency is varied by changing the coupling condenser C. The circuit is of great importance as a frequency reducer; it can be synchronized

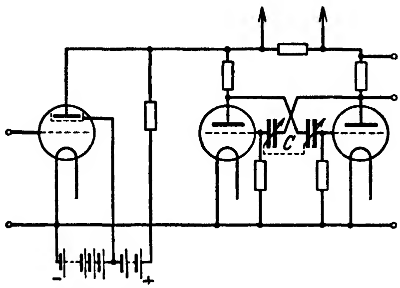


FIG. 247. MULTIVIBRATOR SYNCHRONIZED BY A PRECEDING VALVE WITHOUT REACTION

very well, for instance, as in Fig. 247, by modulation of the anode voltage by the control frequency through a screen-grid valve without reaction. The circuit is, unfortunately, unsuitable for tracing time curves as the curve does not give

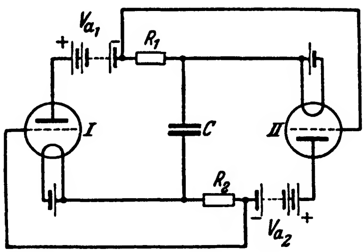


FIG. 248. SYMMETRICAL TIME BASE CIRCUIT USING VALVES (*Frühauf*)

an extended linear range, but is composed of symmetrical impulses of short duration.

The symmetrical valve pulsating circuit of Frühauf[51] (Fig. 248) is a modification of the Abraham and Bloch multivibrator and is derived from it by substituting a direct coupling using separate batteries in place of the resistance-capacitance coupling of the valve. This enables static tracing of the pulsating voltages to be made exactly as with glow lamps.

The use of the Kallirotron in conjunction with the circuit of Fig. 239 is of importance. This circuit, which was developed by E. Hudec (see below, Fig. 251), is really relevant to this section. In order that it shall be better understood it will first be discussed further on.

The combination of charging and discharging valve with the condenser (Fig. 239), already mentioned, constitutes the basis of the most important group of dependent remotely-controlled pulsation circuits. In principle, control can be effected just as well at *L* as at *E*. Control in the charging

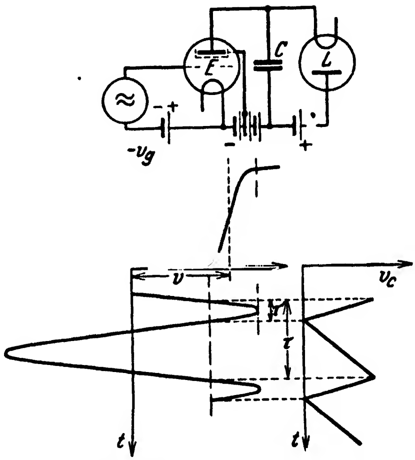


FIG. 249. DISCHARGE CONTROL BY CUTTING OFF THE VOLTAGE

circuit has the disadvantage that there is essentially some distortion of the useful voltage available at the condenser. This disadvantage (e.g. E. Hudec, Ger. Pat. 497473) can only be overcome by the introduction of further valves and circuits, with consequent complication of the equipment, since it constitutes a convenient device for the production of rectangular shaped signals which are required to control dependent pulsations. The control of the discharge in circuits using hard valves exclusively is more complicated than that of gas-filled tubes used in the circuits hitherto described. This requires, firstly, a discharge valve of such high emission that the time of discharge of the condenser *C* is short compared with the useful charging time. At high frequency, therefore, valves of extremely high emission are essential. The circuit must be

arranged so that the grid voltage is sufficiently negative during the process of charging. A positive value which starts the discharge must only exist during the period when the discharge is taking place.

Grid potentials of the form mentioned are most simply obtained by means of voltage tappings as in Fig. 249. A bias voltage ensures that the grid of E becomes positive only during the short period when the momentary value of the alternating

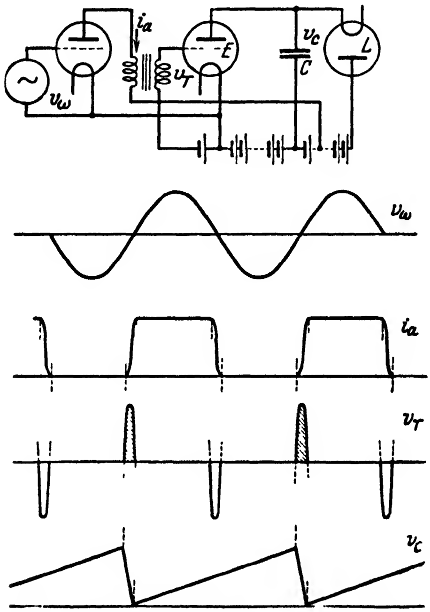


FIG 250 IMPULSE CONTROL OF THE DISCHARGE

control voltage exceeds the value V_g. This period depends on the relation between the two voltage amplitudes. The maximum voltage must bring the discharge valve into operation at once. In order to avoid loading the controlling source, the control circuit must be free from grid current. These conditions can be fulfilled by the selection of a suitable discharge valve, preferably of the screen-grid type. By using a screen-grid valve, the return stroke (fly-back on the oscillograph) is linear and the point at which the pulse starts is well defined.

Fig. 250 shows another way of obtaining the control impulse from an alternating voltage, the so-called impulse method. This

circuit operates with much lower control voltages and is greatly dependent on amplitude. Furthermore, it cannot be extended into the high-frequency range as can be done with the circuit of Fig. 249. The first valve operates in the overloaded state. Its anode current i_a is limited by the saturation value and has a rectangular time characteristic as indicated. The transformer output voltage v_r consists, therefore, of alternative positive and negative potential impulses, the duration of which may be very short corresponding to the time taken by the control voltage v_w to cover the valve characteristic. The result produced is that of definite pulsations of suitable outline as shown

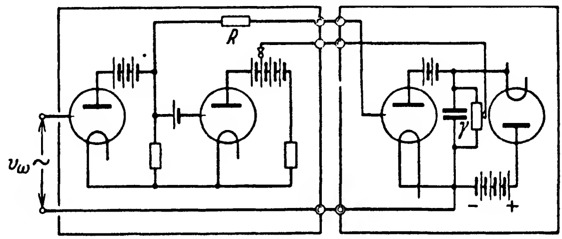


FIG. 251. OLD FORM OF TIME BASE CIRCUIT USING VALVES (*Hudec*)

by the time curve v_c in Fig. 250. A third method is exemplified by the discharge control from the pulses originated by a Kallirotron. This last unit, by its nature, acts as a discharge relay and converts the incoming control voltage into a limited rectangular voltage between definite discharge points. The method is so far unsuitable for simple remote control, as the distance between the zero points would have to be adjusted by artificial bias on the input side of the Kallirotron. E. Hudec adopts the procedure indicated in Fig. 251, therefore, and takes the operating voltage for the Kallirotron from the voltage used at the discharge condenser. A voltage divider provides a reaction to the input grid, whilst the control of the discharge valve by the Kallirotron is effected by the high resistance R in the first control valve. The circuit gives a very good performance, as the control voltage at the grid of the discharge tube has a rectangular characteristic. It can be accurately synchronized by a voltage v_w which is connected to the back-coupling path leading to the input grid of the first valve. At the same time v_w is practically unloaded. The circuit is also suitable for high frequency work in practice, up to

300 000 cyc. In conclusion, it can be said that the introduction of valve circuits for producing saw-tooth oscillations in the range of high frequencies is justified. Oscillations up to $5 \cdot 10^5$ cyc. can be produced with such valve circuits. These are sufficient to make four whole periods of a wavelength of about 100 m. visible. They are therefore sufficiently good for many other high-frequency investigations, though for the production of such high frequencies valves of very high emission are essential. In making comparisons with the flashing circuits previously described it should be stated that those employed for time deflection using hard valves—even of the simple type shown in Fig. 243—are more costly than those using gas-discharge tubes A few more recent circuits are to be found in Chapter IV of the book in connexion with television apparatus. Electrical time deflection for the tracing of predetermined or unpredicted transients is a special sphere of utility for which valve circuits of varied frequency ranges are generally used.

(D) ELECTRICAL TIME DEFLECTION FOR NON-RECURRENT PHENOMENA. The conditions of operation which occur with the tracing of non-recurrent processes are different fundamentally from those which obtain in the registering of periodically recurring events. In the first case, a definite periodic cycle exists in the work circuit as well as in the time base circuit during the whole time the cathode ray is ready to make a trace. When tracing isolated transients, the ray is deflected in the abscissa direction only once for each record. The beginning of the deflection in this direction should coincide with the beginning of the deflection in the ordinate direction. In the tracing of periodically recurring events there is a continual oscillation of the time deflection circuit between two stable positions. In isolated non-recurrent phenomena the ray is deflected once, the time circuit passing from one stable condition into the other, whence it may return to its original condition. The single time sweep is controlled with the assistance of a definite process, e.g. the charging or discharging of a condenser through a resistance, the "time deflection" capacitance consisting of the capacitance of the time deflection plates and of the variable condenser in parallel with them. The charging or discharging takes place logarithmically according to the usual condenser charging characteristic. The change in voltage and velocity of time sweep are not, therefore, constant, but become slower and slower towards the end of

the event. In order that the initial and final scales of time shall not differ too greatly, the first part of the charging curve is used in this simple method, where the curve is almost straight. Usually the time-base voltage employed is sufficiently high so that only a portion of it is required to trace the whole oscillogram. The rest of the voltage change is not used for the oscillogram, since the fluorescent spot lies outside the field photographed.

It is usually desirable to obtain a perfectly uniform time base so that calculations from previous calibration are avoided. In such cases, as also in the case of periodic time sweeps discussed above, a high-vacuum valve with a definite saturation current is used instead of a resistance to obtain a uniform charging current for the condenser. As the time occupied in tracing the oscillogram is relatively short in the photographing of non-recurrent events, the cathode ray must be prevented from remaining stationary at a point on the fluorescent screen, either before or after taking the photograph. This would give rise to premature blackening not only at the point where the spot was stationary, but at all other parts of the photographic medium. In order to avoid accidental blackening, the ray is often deflected off the screen and only brought into the field of the oscillogram by the operation of the time deflection circuit.

As this may result in the loss of part of the process under observation, this loss may be reduced, when tracing a curve of definite polarity, by allowing the ray to make another trace in the ordinate instead of the time direction. To do this the zero line of the oscillogram is displaced outside the outline of the figure. To ensure a minimum loss in the abscissa direction, it is better to deflect the ray to the side of the screen as stated above, and allow it to trace the oscillogram quickly through a special pre-deflection circuit. For this purpose either a potential difference at a special pair of electrodes is caused to collapse quickly, or the time sweep at the deflecting plates is allowed to be advanced. At the same time the releasing devices should be so adjusted that the fluorescent spot is quickly set free from the point outside the screen, where it is located during the quiescent period, to the point on the screen where the oscillogram starts. Usually the subsidiary or preliminary deflection is not quite sufficient to prevent the photographic material from being slightly fogged. As a result of the very protracted period before the ray is brought into action

in comparison with the period of the time sweep, stray electrons, secondary electrons, and X-rays of low intensity are quite sufficient to blacken the photographic material very considerably by their direct or indirect action. Arrangements should therefore be made that as long as a tracing is not taking place, i.e. during the whole period when the ray is deflected off the screen and ready to start a traverse, the ray does not reach any part of the screen which is photographically active. To secure this end, two methods are available: firstly, that in which the cathode ray is switched off during the waiting period and brought into action for a very short period for each tracing; secondly, by ray extinction, a method by which the cathode stream is maintained during the waiting period but is obscured in a particular area. The method of switching the ray on and off can be carried out with the help of mechanically-operated switches or quick make-and-break rotary switches, or alternatively by spark gaps or grid-controlled valves. In earlier arrangements the anode voltage of the cathode-ray tube was switched off. In modern tubes switching the ray on or off without time lag can be arranged by means of the brightness control electrode with a change of only a few volts and very low power consumption. Extinction of the ray is effected throughout by purely electrical means in the low voltage cathode-ray tube, by deflecting the electron jet in front of the anode window during the waiting period, by means of electrostatic or electromagnetic fields and allowing it to be extinguished in this space. At the instant when a tracing is to be made, the fields are allowed to collapse, which operation releases the ray and it can then reach the screen through the anode aperture. The various auxiliary circuits which are required for tracing non-recurrent phenomena must work satisfactorily in conjunction with each other if perfect tracing of the oscillogram is to result. In tracing a figure, the oscillograph must first be prepared for such an operation by removal of either the deflection or extinction of the ray, or by switching it on. When switched on for single time sweep, the abscissa deflection must come into action simultaneously. If, after tracing the oscillogram, the electron jet is not deflected very far from the edge of the oscillogram, and if non-recurrent processes of different nature are to be traced consecutively at short intervals, the ray must be brought back to its original position as quickly as possible. The circuits and their components for control of

the auxiliary circuits are described briefly in the following paragraphs.

Switches consisting of a metal pin dipped in a cup filled with mercury are very often used for controlling the auxiliary circuit of the oscillograph. Usually, however, ordinary switches or keys are sufficient. It is desirable to connect in parallel with switches controlling heavy loads a special circuit consisting of a condenser and resistance in series. When the switch is being closed, an arc is formed in the air between the contacts before they actually touch, or in the case of low voltages at the instant when contact takes place. As a result of the discharge current in the condenser this arc is a good conductor. In particular, the extinction and re-establishing of the arc at the switch is avoided in high-frequency work when the current passes through the zero of the cycle. The resistance in this circuit prevents the duration of the discharge being too short. Experiments show that it should be made of such a magnitude that an initial current of 10 amperes flows through the switch. The capacitance of the condenser should be of the order of 0·01 to 1 μF. Sparks gaps can also be used in place of mechanical switches. If these are connected to low voltages, it is also expedient here to connect in parallel a circuit as described above. Usually spark gaps are energized by raising the voltage slowly to the arcing point, or by raising the potential suddenly to a value exceeding the static arcing voltage.

If the arc is to take place as quickly as possible after the voltage is raised, the gap must be exposed to a powerful source of ionization—an arc or mercury vapour lamp or a radioactive preparation. To ensure immediate arcing, the gap requires an excess of 5–15 per cent of its normal static arcing voltage. In order that arcing may take place with relatively small change in voltage, a bias which is slightly below the static arcing voltage is applied. The biased spark gap only strikes with the correct polarity. In cases where the polarity is not fixed in advance, gaps with three electrodes are used, and these operate independently of polarity. To prevent delayed operation, the electrodes, which get burnt after frequent use, should be kept clean. The function of arc units can be performed by electron tubes which can operate simultaneously as switching devices and as amplifiers. They are used in all cases where only relatively low voltages are available for control. As their efficiency is limited by the emissivity of the cathode, they are

slower in action than spark gaps, the current of which may be quite large. To make up for this, they are independent of external disturbances and generally operate more reliably than spark gaps in cases where continual supervision is not possible. If the discharge current is to be constant during the period of switching on, valves with definite saturation current should be used. Thyratrons can also be used under certain conditions.

The arrangement of the circuit elements in a complete time measuring circuit depends on the nature of the process to be recorded. There are two main groups, i.e. predeterminate and indeterminate processes.* *Predeterminate processes* are those which take place at a time which is definitely selected by the observer through the switching of a certain potential into circuit. *Indeterminate processes*, on the other hand, are those in which the experimenter has no control over the instant of their occurrence, or on the value of the voltage to which they give rise, e.g. transients in conductors caused by atmospheric discharges or by closing or opening a circuit. The time factor of the circuit is of importance in fixing the values of the components; by this factor is implied the period of time from the instant when the control is brought into operation to the instant at which the ray is in a position to record the event under examination. If the ray is switched on mechanically when investigating predeterminate processes, either rotary quick make-and-break or multi-contact switches should be employed to bring into circuit first the electron jet, then the time circuit, and finally the work circuit. With successive switching on of the time and work circuits by a mechanical switch, the minimum variation in time permissible is $1 \cdot 10^{-4}$ sec. Precise adjustment is extremely difficult. Conditions must be such that the work is recorded on the screen of the oscillograph within an interval which is less than the time variable of the switch. For instance it is customary, in order to get the process on the screen with certainty, to allow the time deflection to proceed for $5 \cdot 10^{-4}$ sec. and only bring in the circuit under test $2 \cdot 10^{-4}$ sec. after the time deflection is switched on. More rapid processes can only be traced with sufficiently high time deflection velocity when deflection in two time co-ordinates (see above) is used.

To avoid these difficulties the work and time circuits can be coupled electrically. The switching on of the electron jet

* The subsequent use of these terms in the text imply these definitions.

by means of a quick rotary switch with subsequent switching on of the time circuit now locked with the work circuit can be retained. As a result of the synchronization of work and time circuits, it is possible to work with single time sweeps of very high speed. The switching on period of the ray amounts to 10^{-4} sec. owing to the imperfection of the mechanical switching arrangements. The ray remains effective in the discharge tube for a relatively long period which is quite sufficient with high outputs to fog the photographic material considerably. Mechanical methods of switching on the ray

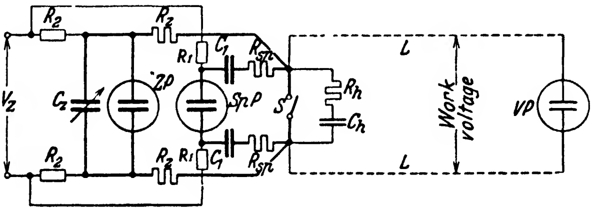


FIG. 252. OLD FORM OF TIME BASE AND STOPPER CIRCUIT FOR PHOTOGRAPHING SINGLE PREDETERMINATE PHENOMENA
(Discharge circuit with resistances)

are not therefore alone suitable for high power electron beams. For low current cathode-ray tubes mechanical switching is in many cases sufficient to prevent premature fogging. Extinction of the ray mechanically has not, so far, met with any success in low voltage cathode-ray tubes.

Inaccuracies of time associated with mechanical switching disappear when this is performed electrically. For example, electrical switching can be carried out in the following manner. A spark gap is interposed in the conductors between the source of anode voltage and the tube. This strikes as a result of an impulse due to an excessive potential, which at the same time sets free the time circuit and, through a delay device, the work circuit. Extinction of the ray is more easily and definitely carried out by means of the brightness control electrode rather than through switching off the anode voltage as just described. In older equipments extinction of the ray is used more frequently than the arrangements in which it is switched off. In this method it is desirable to operate the circuit by which the ray is obstructed together with the time circuit by the same switching control as is used in the work circuit. Fig. 252 shows an arrangement which has been developed by Freundlich

from a circuit by Rogowski and Flegler,[52] and provides a special pair of plates for extinction of the ray. The extinction plates S_pP, the time deflection plates ZP with the time deflection condenser C_z in parallel with them, also the leads L which connect to the measuring plates of the cathode-ray tube, are charged up to the voltage V_z through the resistance R_2. Closing the switch S, in parallel with which is the auxiliary circuit consisting of the condenser C_h and the resistance R_h, causes the condenser formed by the extinction plates to be discharged through the resistance R_{sp}, thus causing the ray to be set free. Simultaneously the discharge of the time deflection condenser C_z through the resistance R_z commences

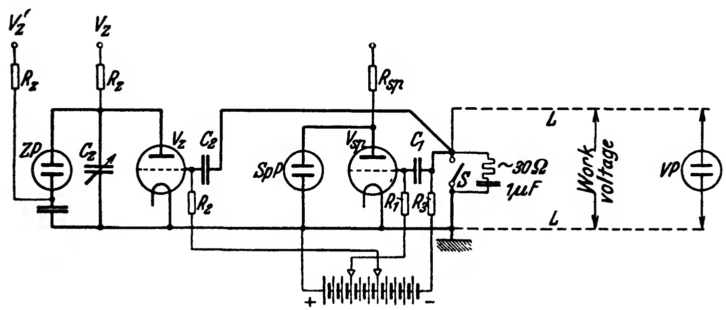


FIG. 253. TIME BASE AND STOPPER CIRCUIT FOR TRACING SINGLE PREDETERMINATE PHENOMENA (DISCHARGE CIRCUIT WITH GRID-CONTROLLED ELECTRON TUBES)

(the capacitance formed by the deflection plates is regarded as being small enough compared with C_z to be neglected). The time constant R_zC_z determines the velocity of the time sweep. It must be suitably chosen for the duration of the event under examination. The time taken for C_{sp} to discharge is determined by the value of R_{sp}. This resistance is required to suppress surges in the extinction circuit which occur on switching on. For the usual arrangement adopted in this circuit, it has a value of 500–1 000 ohms.

The condensers C_1 and the resistance R_1 are only necessary when the ray, after tracing the oscillogram, is to be prevented from remaining in its final position as long as the switch S remains closed. In this case, slight after-glow on the photographic material is possible. The condenser C_1 and the capacitance C_{sp} are charged from the voltage V_z through the resistances R_1 so that the ray is again extinguished independently

of the time during which the switch S remains closed. The time constants R_1C_1 determines the time occupied in resetting. It must be of the order of $\frac{1}{10}$ to $\frac{1}{100}$ of the time of work process. The use of a spark gap in place of the mechanical switch S does not generally necessitate the use of this circuit, since within certain limits the time during which the arc is maintained is affected by the choice of the time constant R_hC_h.

Grid-controlled electron tubes can be used in place of discharge resistances in the circuits mentioned. Such an arrangement is shown in Fig. 253. The valve V_{sp} controls the extinction of the ray and the valve V_z the time deflection. The valves are biased on their grid circuits to a high negative potential from the battery through resistances R_1 and R_2, so that no anode current flows. At the switch S there is also a negative voltage which is higher than the grid voltage. The moment the switch is closed the grids receive a positive impulse which instantaneously restores the valve current, so that the extinction is removed and the deflection brought into operation. The choice of the constants R_1C_1 and the resistance R_{sp} secures the condition that while the switch S is still closed, such a high negative voltage is applied to the grid V_{sp} that the valve is again cut off and the capacitance of the obstruction plates again charges up through the resistance R_{sp}. This again ensures that the oscillogram is not overradiated by the fluorescent spot at the final position, and that the ray is again cut off while the recharging of the time deflection capacitance takes place. Constant velocity of time sweep is the advantage secured by the use of electron tubes with saturated current in time circuits of this kind. Both kinds of circuit given are typical instances where the discharging of a condenser is the essential feature. Arrangements in which the charging of the capacitance of the time circuit is done through the closing of a switch are, of course, possible. Both methods permit of a number of different circuit arrangements which will not be treated further in the scope of this book. To conclude the section on the control of predeterminate phenomena, two other circuits which have been developed particularly for use with low voltage cathode-ray tubes are given.

In Fig. 254 both time and work circuits are switched on by means of a multi-contact key. When contact 2 is opened, the

cathode ray, which in the quiescent state is deflected to the side by a bias voltage, starts its time sweep. When contact 1 is opened a release magnet applies the work circuit to the deflection plates. The shutter of a camera can also be switched open electromagnetically by a contact 4. The exposure time of the shutter must be regulated to the duration of the event under examination in order to avoid after-glow on the plate from the return path of the ray.

With this method care should be taken that the time con-

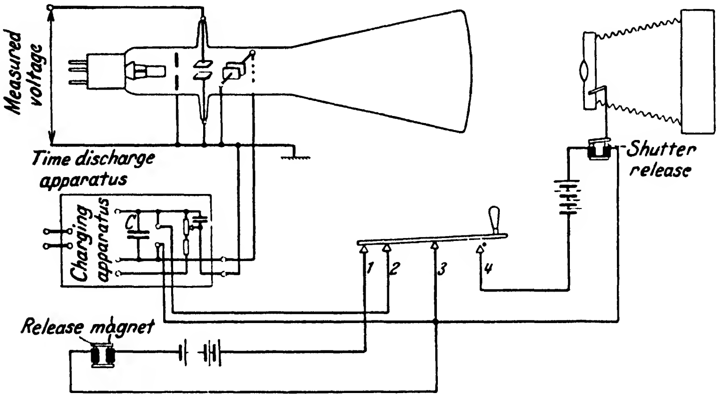


FIG. 254. CIRCUIT FOR TRACING PREDETERMINATE PHENOMENA WITH LOW CURRENT CATHODE-RAY TUBES

stants of the various operating relays are correctly synchronized with each other, and that tracing only takes place when the aperture of the camera is fully open.

Fig. 255 shows a circuit operated by a key in which Wehnelt cylinder control is provided to secure extinction of the ray. By depressing the contact arm, which is movable about its fulcrum G, contacts 1 and 2 are first opened, causing the bias on the Wehnelt cylinder to be reduced to the value necessary for focusing the ray. The additional bias supplied by a battery is removed. By depressing the contact arm still further, contacts 7 and 8 are closed, which charges the time sweep condenser, and the cathode ray hitherto deflected in the stationary position outside the screen starts its time sweep. Simultaneously, or slightly later, the voltage under test is connected by the contacts 5 and 6.

In tracing indeterminate processes it is no longer possible to

control the time circuit (time deflection and ray extinction circuit) and the work circuit by the same device. With each tracing, the transient must itself set the cathode ray in operation, and this must be done as far as possible without any time lag, otherwise a portion of the transient will have already been received before the ray is ready to trace. Switching devices which include moving parts cannot be used for this purpose on account of their inertia.

Fundamentally, there are two different ways of putting the

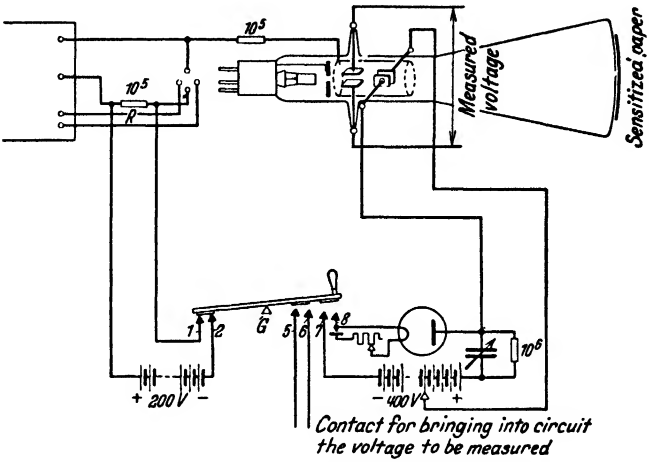


FIG. 255. TIME DEFLECTION AND ARRANGEMENT FOR RAY EXTINCTION FOR SCREEN CONTACT PHOTOGRAPHY OF SINGLE SWEEP PREDETERMINATE PHENOMENA

oscillograph in a condition to trace indeterminate phenomena. In the first method the ray is controlled directly by the work circuit. In the second the work circuit excites an independent relay which is free from inertia and which in turn controls the time circuit.

The first method can be employed with the assistance of the special tube shown in Fig. 158, which has been discussed previously.(53) As soon as the work voltage is applied to the pair of ordinate plates which are permanently connected to the external circuit, the current to the guard ring electrode ceases, and the drop in voltage across the resistance shown in Fig. 158, hitherto due to ray current, is altered. This change in voltage which is tapped off at the terminal K must naturally

be used to release a single sweep in the abscissa direction. This can be carried out by using the voltage variation as a control voltage for one of the pulsating discharge arrangements previously discussed.

Spark gaps and electron tube discharge relays have proved suitable as independent relays for the second method. Spark gaps, it is true, have a very small time lag, but require relatively high voltages for excitation. As the spark-gap voltage with low time lag is the same as that at the time plates, and since this plate voltage, especially in gas-filled cathode-ray tubes, cannot be increased as desired, if the possibility of passing a glow discharge is to be avoided, these relay devices cannot in general be used for low voltage cathode-ray tubes.

The second type of independent relay, the electron tube discharge relay, is based on the principle of direct-coupled reaction. The Kallirotron, previously mentioned, is a circuit involving the discharge relay which has not so far been developed for single time sweeps in recording indeterminate non-recurrent phenomena. Various forms of discharge relay for tracing such transients have been developed in recent years from the Kallirotron. The single grid discharge relay, by Freundlich and Knoll, is the most modern of its kind and one which responds to positive as well as negative impulses, and at the same time has an extremely low delay in response. Also, in this relay, the extinction circuit and the time circuit are combined together with the actual discharge circuit in one unit. It represents a universal equipment for tracing the most rapid as well as the slower predetermined periodic or indeterminate non-recurrent phenomena.

Fig 256 shows a circuit arrangement of this discharge relay. In the centre of the circuit diagram are the two discharge valves 1 and 2 with direct-coupled reaction. In the quiescent state the grid current of valve 2 flows from the battery through the point A and the grid resistance R_{g2}, so that the grid is slightly biased positively. Valve 2, therefore, functions with full emission current, and a considerable voltage drop exists across R_2. The grid of valve 1 is biased negatively through resistance R_1', so that its emission is cut off. Assuming now that a negative potential impulse is applied to the point between C_{st} and C_3, the grid of the valve 2 will suddenly become negative. This is subject to the condition that C_{st} is of the same magnitude as the total capacitance to earth at this point,

since the voltage division caused by these two capacitances determines the grid voltage on the valve. The capacitance to earth is shown by the dotted lines and is marked C_2'. It comprises the anode capacitance of the valve 1, the grid capacitance of valve 2, and the unavoidable capacitance to earth of C_2, as well as the conductors. The corresponding capacitance C_1' at the valve 1, is due to the same factors. The latter is, however, augmented by the capacitance of the extinction plates. With a negative impulse, the current of valve 2 is interrupted and the condenser C_1' is charged through R_2.

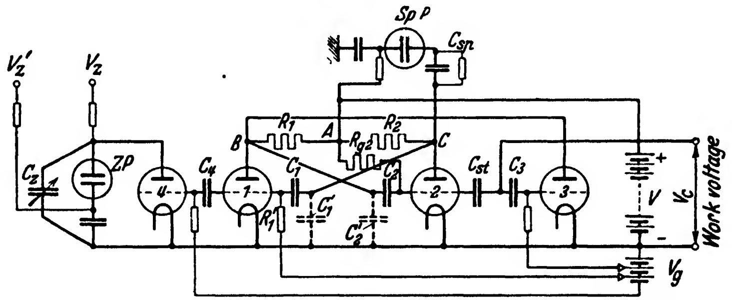


FIG. 256. SINGLE GRID VALVE BASE BY FREUNDLICH FOR TRACING PREDETERMINATE AND UNPREDICTED PERIODIC AND TRANSIENT PHENOMENA

Simultaneously the grid of valve 1 becomes positive so that the anode current is established in it. As a result, the condenser C_2' is discharged whereupon the grid of valve 2 again receives a negative impulse. If, in the meantime, the negative potential impulse decreases or possibly becomes a positive one, the anode current of valve 2 is still cut off. The change in potential of the point C is employed to raise the potential of the right-hand extinction plate through the condenser C_{sp} to the same potential as the left-hand plate. The cathode ray which was at first deflected now becomes free as a result of this operation. In addition, the grid of the time deflection valve 4 becomes positive simultaneously with the grid of valve 1, so that the time-deflection valve discharges the time condenser and the time sweep takes place. Naturally the extinction plates can also be discharged through an electron tube, in which case the grid of this tube should be connected in parallel with the grid of valve 4. If a positive voltage appears, valve 3 comes into operation. Its anode current increases and discharges C_2';

consequently, a negative impulse is given to grid 2, and so on, as described above. If the relay is discharged, the grid of valve 2 again becomes positively charged through R_{g2} and the relay is reset. The time constant C_2R_{g2} gives the resetting period. The discharge time, i.e. the time during which the point C undergoes a complete change in potential, depends on the capacitance C_1' and the resistance R_2. As the lower limit of this capacitance is about 100 $\mu\mu$F., it is essential that the resistance R_2 should be made as small as possible for the most rapid tracings. Quantitatively the conditions are somewhat as follows. Assume that valve 2 is formed by two efficient valves each having an anode dissipation of 25 watts and connected in parallel. These valves with positive grid bias and anode voltage of about 120 volts each have an anode current of 200 mA., so that the current in R_2 amounts to 0·4 ampere. About 200 volts is necessary to extinguish the ray, whence from considerations of the voltage drop, the value of R_2 is about 500 ohms. It is convenient to use a tungsten filament lamp in this case with a consumption of 75 watts. The time constants can now be calculated thus

$$\tau = R_2 \,.\, C' = 500 \,.\, 100 \quad 10^{-12} = 5.10^{-8} \text{ sec.} \quad . \quad (51a)$$

As some three time constants must be taken into consideration by the time the relay is completely reset, i.e. by the time the voltage equalization is complete between C and A, when the extinction plates set the ray free, the resultant minimum time lag of the discharge relay is $1{\cdot}5 \,.\, 10^{-7}$ sec. In so far as longer time lags are permissible in the tracing of less rapid processes, any desired time lag can be secured for the relay by suitable substitution of the valves, capacitances and resistances in the circuit. The circuit is therefore suitable in the same way for use with high and low voltage oscillographs.

(E) TRACING CHARACTERISTICS BY ELECTRICAL TIME DEFLECTION. Tracing characteristics is a special application of electrical time deflection. Whereas in the tracing of oscillograms, previously described, the ordinates were dependent merely on the process recorded and the abscissae on the time, in tracing characteristics the ordinates as well as the abscissae depend on the process examined and are variable with time. The result is that the oscillogram obtained shows merely the way in which one variable which is recorded in the ordinate direction

is related to a second variable recorded in the abscissa direction. The time co-ordinates disappear from the oscillogram* and the effect of time is limited merely to differences in brilliancy of the various parts of curve registered. There is very little change in brilliancy even when sinusoidal deflecting voltage is used. There is only a slight thickening at the extremities of the characteristic under observation. The sensitivity of the cathode-ray tube is in practice almost linear, and most modern tubes fulfil this condition, so that characteristics with linear ordinate and abscissa scales can be produced directly and there is no necessity to retrace them again later.

The inertia of the cathode-ray tube which is low enough to be ignored permits of the tracing of the characteristic at the rate of 20 times per second, provided that the circuit under investigation does not limit this by introducing a time lag of its own. These characteristics, therefore, appear to the eye as standing or stationary figures. When several traverses per second of the characteristic are made, the dynamic characteristic and not the static one obtained by point to point measurements is recorded. The tracing of the dynamic characteristics is of extreme importance. The study of dynamic characteristics, the outline of which, especially when overloading takes place, can only be appreciated in theory with difficulty, is of much greater importance in judging units than a knowledge of their static characteristics. Static characteristics can also be traced by means of the cathode-ray tube by dispensing with the repetition of traverse and using very slowly changing deflection voltages. In the latter case, it is desirable to use screens which have a strong after-glow. The cathode-ray tube makes possible in the simplest manner, the recording of operating characteristics which exist at a certain frequency —in this case a sinusoidal voltage should be used for deflection —and also the observation of dynamic characteristics in which many frequencies are present. This property deserves the greatest attention since such characteristics can scarcely be determined from theoretical considerations, or at any rate only with the expenditure of a great deal of time and labour. It would be difficult to find a method of making measurements equally as good as the cathode-ray tube, particularly for recording patterns which are often complicated

* Lissajou's figures can also partly be looked upon as characteristics, in so far as they satisfy the characteristic conditions stated.

by a large number of different frequencies. Here it must be remembered that the tracing of voltage and current characteristics which cannot be directly connected involves the use of coupling transformers described previously in detail. When tracing characteristics, the voltage or current concerned must not be disturbed and the power consumed for tracing must not have any effect on the process being measured. The magnitude of the power transferred from the circuit under test will determine whether one or more stages of amplification will have

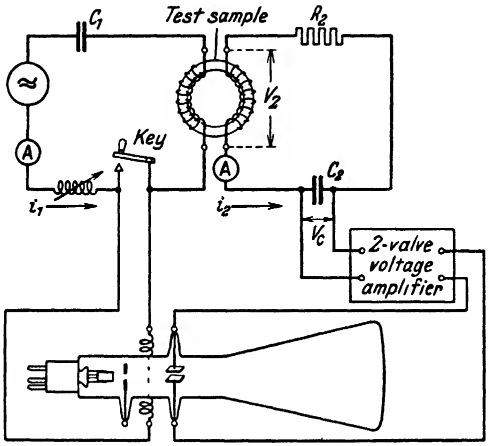


FIG. 257. ARRANGEMENT FOR TRACING MAGNETIZING CURVES

to be connected between this circuit and the cathode-ray tube. The following example explains these relations in more detail. The circuit of Fig. 257 shows a device for tracing magnetizing curves and was developed by Krüger and Plendl.[54] They use a test specimen with a closed iron core in order to obtain uniformity in the lines of force through the iron. This iron core is excited by an alternating current i_1 which traces simultaneously an oscillogram co-ordinate by magnetic deflection. The inductance of the variometer is chosen so as to be high compared with that of the iron core, in order to obtain a sinusoidal magnetizing current under any circumstances. To deal with high currents which carry the iron into the region of saturation, the primary circuit is tuned by the capacitance C_1 and the variometer to the approximate frequency of the a.c. generator. The voltage induced by

the flux in the secondary winding of the magnetic circuit with N_2 turns serves to produce the second co-ordinate of the oscillogram. It is displaced at first by 90° with respect to the ordinate. A phase-shifting circuit composed of the high ohmic resistance R_2 and the condenser C_2 is provided in the secondary circuit to correct this phase displacement. R_2 should be chosen high enough to avoid appreciable reaction between the secondary and primary circuits. The condenser C_2 should be chosen so that its capacitance is negligible compared with the ohmic resistance R_2. Consequently, the voltage across the terminals of the condenser is

$$V_c = \frac{1}{C_2} \cdot \int i_2 dt = \frac{-N_2}{C_2 R_2} \int \frac{d\phi}{dt} = \frac{-N_2}{C_2 R_2} \cdot \phi \quad . \quad (52)$$

The voltage is therefore proportional to the magnetic flux ϕ, and consequently the deflection voltage at the cathode-ray tube is proportional to the induction B. The condenser integrates independently. The instantaneous value of its terminal voltage gives a measure of the instantaneous value of the alternating flux in the iron core. In designing the secondary circuit mentioned above, the condenser voltage has quite a relatively small amplitude. The two-stage amplifier shown in Fig. 257 ensures that the condenser voltage is amplified without distortion to a degree suitable for deflection. Fig. 258 shows a hysteresis curve obtained with the arrangement described. The axes of co-ordinates visible in the picture were obtained by switching off in quick succession, the ordinate and abscissa deflection. Valve characteristics can be obtained in a similar way. In this case it is possible to trace the characteristics by selecting combinations of the co-ordinates of grid voltage anode current, anode voltage, grid current, auxiliary grid voltage, and so on. To obtain the actual operating characteristic of the circuit under examination, the latter must not be loaded or altered in any way to an appreciable extent through the addition of the cathode-ray tube circuit. If, for instance, the anode or grid current is to be traced by means of the voltage drop across a resistance, the latter must be small compared with the internal resistance or grid resistance of the valve investigated. Except in the case of larger transmitting valves the voltage drop must be insufficient to produce deflection of the ray directly. The addition of an amplifier in this case enables large characteristic figures to be traced

without distortion. The amplifier must, of course, transmit uniformly the harmonics contained in the curve. Fig. 259 shows a static valve characteristic traced with slow deflection frequency and a dynamic characteristic obtained with fairly high frequency. The simple examples shown may suffice to indicate the fundamentals involved in tracing such characteristics. Details of circuit arrangements will be found further on in the section dealing with the uses of the cathode ray tube as a measuring instrument. The various methods referred to in this section are suitable for use with voltages whose maximum amplitude is kept constant. For certain uses, however, the amplitude must fluctuate periodically, i.e. the alternating deflection voltage is modulated to an extent of anything up to 100 per cent according to the degree required. The use of modulated deflection voltages for tracing characteristics was described by the author in connexion with the tracing of the characteristics of rectifiers.[55] In consequence of the freedom of the cathode-ray tube from inertia during operation, it is possible to record visibly several characteristics simultaneously. Tracing two characteristics simultaneously is of great value when working tests or comparisons are being made during the manufacturing process. According to Hollmann's method,[56] several characteristics can be obtained by connecting to the deflection plates alternately the voltages which originate in the units under investigation with the assistance of rotary commutators. If the speed of revolution is sufficiently high and they are not synchronized with the deflection frequency, then by persistence of vision, the portions of the characteristic unite so closely that a closed curve is formed. A variation of the same idea consists in tracing alternately the various characteristics in their entirety, provided, of course, that at least 16 images per second fall on each characteristic in order to obtain figures which appear stationary even with screens having no after-glow.

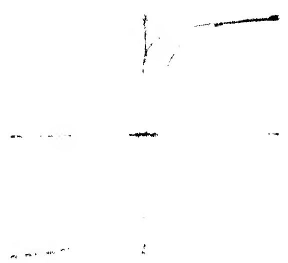


FIG. 258. HYSTERESIS CURVE

In many cases the characteristic to be traced is not identical with the path of the cathode ray. In fact, it is more usual for the desired characteristic to appear as the limiting curve formed by the peak values of a periodic oscillation, the period of which is very small compared with the total length of the oscillogram. In the limit, the succession of single oscillations becomes a luminous surface which increases the readable accuracy of the characteristic to a maximum. A typical example of the nature of such curves is the tracing of frequency characteristics.

FIG. 259. STATIC AND OPERATING CHARACTERISTICS OF A VALVE

The tracing of resonance curves was carried out with the aid of rotary potentiometers very early in the development of the technique.(57) The rotary potentiometer combined with a variable condenser used by the authors named is shown diagrammatically in Fig. 260. The introduction of this unit into the circuit is shown in Fig. 261. For each position of the ray (potentiometer voltage) there is a corresponding value of capacitance of the variable condenser. This condenser is included in the oscillatory circuit of the transmitter. The frequency scale is more or less extended according to the relation between the capacitance of the rotary condenser to that of the oscillatory circuit. It is important that the transmitter should be so connected and designed that no appreciable amplitude variation in the high-frequency oscillations produced occurs within the frequency interval covered. As a result of the transmitted oscillation of fluctuating frequency being applied to an oscillatory circuit or to a complete high-frequency amplifier, and the resulting voltage being applied to the ordinate pair of plates of

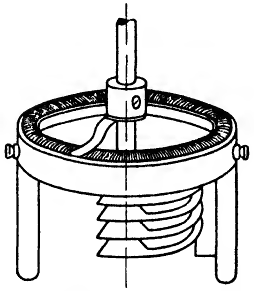


FIG. 260. CONDENSER ROTARY POTENTIOMETER (*E. Marx and F. Banneitz*)

the cathode-ray tube, the response curve appears on the screen as the limiting boundary of a surface on both sides of the zero line. For clarity it is desirable, if possible, to cover the area which is below the zero line.

The same method is used with low-frequency amplifiers in making frequency distortion visible. For this purpose, the contrivance of Fig. 261 needs only to be altered in so far as the rotary condenser is connected in the oscillatory circuit of

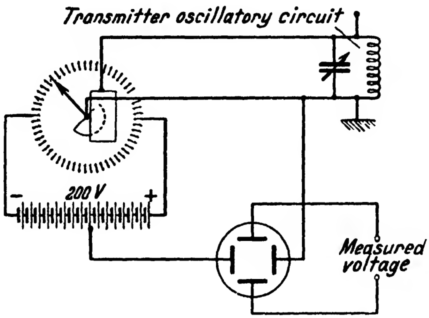


FIG. 261. DEFLECTION ARRANGEMENT FOR MAKING FREQUENCY CURVES VISIBLE

an audio-frequency beat generator.[58] In order to make the frequency curve as clear as possible, especially in the low-frequency range, it is advisable to make the number of revolutions of the rotary unit as low as possible even at the expense of steadiness of the picture. For instance, it is not possible by the method described to make loudspeaker curves or curves with decided self-resonance visible except with a considerable after-glow on the screen, because the times of formation and disappearance of the resonance point are greater than the time available for the rapid traverse of the corresponding frequency band.

V. PHOTOGRAPHIC AIDS TO OSCILLOGRAPHY

1. **General Considerations.** Judgment of the outline of an event as a function either of time, or of a second event, is possible with sufficient accuracy in many cases by visual observation of the oscillogram on the fluorescent screen. Very often it is desirable, however, to keep a record of the traced oscillogram.

The making of a permanent record of a traced oscillogram is almost always secured by photography. Direct records are particularly useful if quantitative evaluation, either by calculation or by graphical methods of the oscillogram, is necessary. This can be carried out much more simply and with greater accuracy on a photograph than on the screen itself. Graphic evaluation of the oscillogram, which has to be deduced from the outline, e.g. Lissajou's figures, is either impossible or possible only with considerable difficulty on the oscillogram as it appears on the screen. The quantitative comparison of a large number of oscillograms of the same process taken under different experimental conditions is also possible only with a photographic record.

Direct registration of the oscillogram becomes necessary when the process to be traced occurs only once and cannot be repeated. The registration of unpredictable events in particular is possible only by means of photography. As the oscillogram outline is traced only once by such events, extended indirect observation and examination of the oscillogram is not possible on account of the short duration of the image, except in the case where fluorescent screens with very long after-glow are employed.

Methods of recording photographically differ in the way in which energy conversion takes place and the point at which the oscillogram is recorded. As a result, two methods are possible—

Internal photography, which includes electron ray photography in a high vacuum.

External photography, which comprises electron-ray photography through a Lenard window, screen contact photography, and photography with camera lens.

In the two processes first mentioned the kinetic energy of the high velocity electrons is used to act on the photographic material directly. In screen contact photography and tracing with camera and lens the kinetic energy is converted first of all into luminous energy; the light emitted by the screen acting on the photographic plate. Whereas with internal photography the action on the photographic material occurs inside the oscillograph, the sensitive surface in electron-ray external photography is blackened by electrons outside the oscillograph, the electrons passing through a thin foil window. In the contact process, the light-sensitive material is applied

directly to the electron window. In screen contact photography and in tracing with a camera lens, the action on the photographic film occurs outside the oscillograph. In screen contact process as in the Lenard process, the photographic film is pressed directly on to the luminous screen excited by the cathode rays. In tracing with a camera lens the oscillogram outline, which appears on the luminous screen, is photographed in the usual way.

Qualitative as well as quantitative comparison of the four tracing processes is possible in the following way according to Knoll.[59]

The criteria of the quality of an oscillogram and therefore of the efficiency of the whole apparatus are—

1. The maximum tracing velocity $v_{s\,max}$ (km. per sec.), the velocity at which the tracing spot produces a blackening of 0·1 on the oscillogram surface.

2. The number of points on the image

$$n_b = MZ/d_s^2$$

M and Z are respectively the length and breadth of the luminous track.

d_s = tracing spot diameter in cm.

3. The maximum sensitivity of measurement for electrostatic deflection $a_{v\,max}$ (deflection cm. per volt).

For magnetic deflection $a_{m\,max}$ (deflection cm. per ampere turn).

4. The resolving power

$$\delta = (v_{s\,max}/c)n_b = (v_{s\,max}/c)\,(MZ/d_s^2) \qquad . \qquad . \qquad (53)$$

where c = velocity of light.

Of these values d_s and $v_{s\,max}$ are important in deciding the relative value of the method of tracing used and the efficiency is determined by them. The velocity of the tracing spot is

$$v_s = d_s/t \qquad . \qquad . \qquad . \qquad . \qquad . \qquad . \qquad . \qquad (54)$$

and $t = d_s/v_s$ indicates the time during which a surface element of the screen is exposed to the rays in the middle of the tracing stroke. At the same time, if i_s is the tracing current and e the electronic charge, the number of electrons falling on unit area at the centre is

$$n_1 = \frac{i_s}{\pi d_s^2/4} \cdot t = \frac{4 i_s}{\pi e \,.\, d_s v_s} \text{ electrons per unit area} \quad (55)$$

Further, the anode potential of the cathode-ray tube in volts is indicated by V_b, and the energy density in energy quanta per cm.[2] sufficient to cause blackening to the extent of 0·1 on the silver bromide emulsion corresponding to maximum tracing velocity $v_{s\ max}$ by N.* If, now, $v_s = v_{s\ max}$, n_1 will be proportional to an energy density N, which in accordance with definition is that required to produce blackening to the extent of 0·1, which is just perceptible to the eye. In this case, therefore, $N = k \cdot n_1$ (electrons per unit area).

Assuming that the minimum energy quantum to which the silver bromide grain reacts is 2 electron volts, we may take this as the unit of energy for N, so that $k = V_b/2$. By substituting $2N/v = n_1$, i_s in microamperes, and d_s in centimetres, with $e = 1{\cdot}59 \times 10^{-19}$ coulombs, we get from equation (55) the maximum tracing velocity. Now, in the case of an external recording arrangement, the decrease in energy density caused through the intervening media between the focal plane of the electrons and the silver bromide emulsion must be denoted by the factor η_1. From equation (55) we have then

$$v_{s\ max} = 4.10^7\ (i_s/d_s) \cdot V_b \cdot (\eta_1/N)\ \text{km. per sec.} \qquad (56)$$

The way in which the maximum attainable velocity varies with the method employed, depends on the value of η_1/N, which has a different value for each process of tracing, the significance of which results from the following considerations.

The efficiency of a method of tracing depends on the completeness of the conversion of electronic energy into photochemical energy. With electron-ray photography, a good proportion of the available energy is converted partly into electron and wave radiation and is lost in the gelatine. The remainder is used partly in ionization of Ag.-Br. molecules of which only those on the surface of the silver bromide grains are subject to the action of the developer. With screen photography, the electronic energy must be converted first into luminous energy. In this process the energy conversion amounts to 1–10 per cent, according to the intensity. A large portion of the electron energy also is lost in the gelatine. Another portion brings about the ionization of the Ag.-Br. molecules

* N may be taken as a constant, since the action of the electron rays on the photographic material, even in the lower intensity range, depends, as distinct from photography with light rays, only on the number of energy *quanta* falling on the photographic film and not on the rate at which they follow one another.

at the surface of the silver bromide grains by photo-electric action. When it is remembered that in both methods, all the electrons striking a grain which has already received an impact, represent an energy loss, the efficiency must naturally be very low and vary with the intensity.

As the photographic plate is not responsive when the minimum energy density necessary for excitation drops below a certain value, the efficiency must be regarded as the ratio of two energy densities rather than the ratio of the energy itself in the two cases. The energy density N_1, which is necessary to give a photographic density 0·1 in the investigation in question, is therefore compared with the energy density N_2 (assumed constant) which theoretically is sufficient to give a photographic density of 0·1 on a sensitive photographic plate. If, in addition, as shown in equation (56), the decrease in energy density between the focal plane of the electrons and the silver bromide emulsion is taken into consideration, then the efficiency of the method of tracing becomes

$$\eta = (N_2/N)\eta_1 \qquad . \quad . \quad . \quad . \quad . \quad (57)$$

The number of silver bromide grains which must be developed per unit area to produce a photographic image which is just visible is about $1/10^4$ of the total number of grains in the emulsion. In determining the constant N_2, one must reckon with a total number of grains which is equal to 10^9 per cm.^{2} (average value for sensitive plates). As it is known from photo-chemical investigations that in a given case the energy of one light quantum is sufficient to make a grain of silver bromide capable of development, N_2 can be given as

$$10^9 \,.\, 10^{-4} = 10^5 \text{ (light quanta per cm.}^2\text{)} \qquad . \quad . \quad (58)$$

If it is assumed that a light quantum corresponds to about 2 electron volts,* N_2 can also be expressed in terms of electrical energy quanta as

$$N_2 = 10^5 \text{ (2 electron volts per cm.}^2\text{)} \qquad . \quad . \quad (59)$$

Therefore $$\eta = 10^5\eta_1/N \qquad . \quad . \quad . \quad . \quad . \quad (60)$$

From this, the absolute value of η can be calculated after taking into consideration the constant N for various silver

* An $h\nu$ of the wavelength 436 mμ corresponds to an energy of 2·5 electron volts; an $h\nu$ of wavelength 546 mμ (green Hg. line) to an energy of 2·3 electron volts.

bromide emulsions or luminous substances. In the next section the importance of the four methods of tracing mentioned is made clear.

Generally, each photographic material will give an optimum small value of N according to the method of tracing employed, since the electron sensitivities differ from the luminous sensitivity. In a comparison of methods of tracing, therefore, one and the same silver bromide emulsion must not be used for each method; on the contrary, the most favourable silver bromide emulsion must be used as a basis for comparison. In particular, special methods of activation must be considered for increasing the electron or luminous sensitivity of the photographic emulsion. Generally, however, comparisons of efficiency will be made with commercial emulsions, as these, for practical reasons, are almost exclusively used for cathode-ray tubes. As the efficiency investigations so far carried out relate only to oscillographs with high exciting voltages (70 kV.) for tracing of the fastest processes, the comparative efficiency values obtained by these investigations are only valid primarily in this voltage range. By suitable conversion they are valid for low anode voltages such as occur particularly with low voltage cathode-ray tubes. This is particularly the case with the magnitude N, the variation of which with anode voltage in the various methods of tracing will be discussed later on.

With electron ray photography in high vacua, the energy of the electrons available becomes directly effective photochemically on the silver bromide emulsion. Therefore $\eta_1 = 1$. For $\eta_1 = 1$ and $V_b = 70$ kV., the values of $v_{s\ max} \cdot i_s$ and d_s were taken from experimental oscillograms and the efficiency values given in Table II were obtained therefrom.

TABLE II

PHOTOGRAPHIC SENSITIVITY AND EFFICIENCY WITH ELECTRON RAY PHOTOGRAPHY IN A HIGH VACUUM (INTERNAL PHOTOGRAPHY)

(1 energy quantum = 2 electron-volts)

Emulsion	$N \cdot 10^{-9}$ Energy Quanta per cm.^{2}	$\eta (= 10^5 \frac{\eta_1}{N} \cdot 10^9)$ (Efficiency)
Agfa positive stock	42	2·4
Agfa X-ray stock	12	7·9

For the calculation of the efficiency of electron ray photography through a Lenard window (external photography), an arrangement, consisting of steel bars with a mesh drawn over them and carrying the air-tight foil, was used. In this case

$$\eta_1 = \eta_{\varepsilon 1} \cdot \eta_{\varepsilon 2} \quad . \quad . \quad . \quad . \quad . \quad (61)$$

where $\eta_{\varepsilon 1}$ signifies the electronic energy passed by the mesh and η_2 that transmitted by the foil. For a filter mesh with 42 per cent free surface $\eta_{\varepsilon 1} = 0{\cdot}42$. With an electron velocity of 70 kV. the coefficient of absorption for cellophane is $a = 390$. Therefore, for cellophane foil 15μ thick

$$\eta_{\varepsilon 2} = e^{-390 \,.\, 0{\cdot}0015} = 0{\cdot}56 \quad . \quad . \quad . \quad (62)$$

For 70 kV. therefore,

$$\eta_1 = 0{\cdot}42 \,.\, 0{\cdot}56 = 0{\cdot}235 \quad . \quad . \quad . \quad (63)$$

For higher exciting voltages, η_2 and therefore η_1 increases rapidly. As the electron velocity lost in the foil is small enough to be ignored, the same values for N are valid for the calculation as in the case of high-vacuum photography (Table III)

TABLE III

EFFICIENCY OF ELECTRON RAY PHOTOGRAPHY (EXTERNAL PHOTOGRAPHY)

Emulsion	$N \,.\, 10^{9}$ (Energy Quanta per Cm ^{2})	$\eta(- 10^5 \frac{\eta_1}{N} \; 10^6)$ (Efficiency)
Agfa X-ray film. . . .	12	1 9
Silver bromide paper ("Oszillox")	12	1 9

In screen photography (external photography) the image is obtained by pressing the light sensitive film on to the outside of the screen, the thickness of the screen carrier being assumed small. Hence, the relation

$$\eta_1 = \frac{\text{Intensity of illumination of image surface on silver bromide emulsion}}{\text{Intensity of illumination at the focal plane of the electrons}} \quad . \quad (64)$$

The light energy incident on the electron screen surface,

which is passed on to the silver bromide emulsion, must penetrate parts of the luminous surface (of thickness d_2), and the screen carrier (thickness $d_1 < 0{\cdot}5$ mm.). Assuming a window thickness $d_1 = 5{\cdot}10^{-3}$ to $5{\cdot}10^{-2}$, values which are valid only for high-tension cathode-ray oscillographs with supported screen contact window, and a luminous screen thickness of $d_2 = 0{\cdot}0015$ cm., we have, allowing for light absorption and diffused reflection (4 per cent at each surface of the window)

$$\eta_1 = e^{-a_1 d_1} \,.\, e^{-a_2 d_2} \,.\, 0{\cdot}96^2 \sim 0{\cdot}6 \qquad (65)$$

Therefore the efficiency values for screen contact photography at 70 kV. anode are those shown in Table IV.

TABLE IV

PHOTOGRAPHIC SENSITIVITY AND EFFICIENCY WITH SCREEN CONTACT PHOTOGRAPHY (EXTERNAL PHOTOGRAPHY)
(1 energy quantum — 2 electron volts)

Emulsion	$N \,.\, 10^{9}$ (Energy Quanta per cm.²)	$= 10^5 \,.\, \frac{\eta_1}{N}\Big) 10^6$
Agfa isochromatic film	190	0·31
Silver bromide paper ("Oszillox")	83	0·72

The efficiency can be also expressed for the last method of tracing referred to, i.e. in the case of tracing with camera lens, in the following way. It is assumed that the outside of the luminous screen will be photographed. In such case, the light energy available on the screen which passes on to the silver bromide emulsion must penetrate parts of the luminous surface, window and lens. Therefore

$$\eta_1 = \frac{E'}{E} = \frac{\text{Intensity of illumination of image on silver bromide emulsion}}{\text{Intensity of illumination on the focal plane of the electrons}} \qquad (66)$$

If the focal point of the electrons is regarded as a self-luminous circular disc for which the Lambert cosine law holds good, the total light flux emitted is ϕ, and if I indicates the intensity of the source of light,

$$\phi = \pi I \qquad (67)$$

If B is the illuminating power of the electron spot on the screen, ω_1 the solid angle in which the radiation of this spot takes place, ω_2 the solid angle embraced by the objective, and $\beta = dr/ds$ (d_p the image diameter), the image scale

$$E' = B \cdot \omega_2 (1/\beta^2) \qquad (68)$$

and

$$E = B \cdot \omega_1 \qquad (69)$$

as long as $\omega_2 \ll \omega_1$, then

$$\omega_1 = \pi \qquad (70)$$

can be substituted in equation (66) and

$$E'/E = K_1 K_2 \omega_2/\pi\beta^2 \text{ results} \qquad (71)$$

The factors K_1, K_2 represent losses in the window and the lens. K_1 corresponding to the factor η_1 (see screen contact photography), can be considered in practice to be 0·6, whilst K_2, according to the type of objective used, may vary between 0·9 (for simple objectives) and 0·4 (for combinations). If u indicates the angle of divergence between the extreme ray of the solid angle and the axis of the lens, i.e. $\sin u = A$, the aperture on the object side, A' indicates the lens aperture on the image side where $\beta = A'/A$, then

$$\eta' = \frac{E'}{E} = \frac{K_1 K_2 \pi \sin^2 u}{\pi\beta^2} = \frac{K_1 K_2 \cdot A^2}{\beta^2}$$
$$= 0{\cdot}6 K_2 \cdot A'^2 \qquad (72)$$

Accordingly, η_1 is dependent essentially only on the square of the aperture A' of the objective which is on the image side; its absolute magnitude, for example, for two selected lenses at different image scales, becomes—

Zeiss Tessar.

$$f = 100 \text{ mm.}$$

Light intensity

$$1/3{\cdot}5 = 2h/f$$

Radius of effective aperture

$$h = 100/(2 \times 3{\cdot}5) = 14{\cdot}3 \text{ mm.}$$

$$K_2 = 0{\cdot}6$$

$$A'^2 = 14{\cdot}3^2/b^2$$

(*a*) Image scale $\beta = 1:1$, distance between lens and film $b = 2f = 200$

$$\eta_1 = \frac{0{\cdot}6 \,.\, 0{\cdot}6 \,.\, 14{\cdot}3^2}{200^2} = 0{\cdot}00184$$

(*b*) Image scale $\beta = 1:5$ (reduction), $b = 6/5$

$$f = 120 \text{ mm.}$$

$$\eta_1 = \frac{0{\cdot}6 \,.\, 0{\cdot}6 \,.\, 14{\cdot}3^2}{120^2} = 0{\cdot}0051$$

Special Objective, Astro R.K. Lens.

$$f = 75 \text{ mm.}$$

Light intensity

$$= 1/1{\cdot}25$$

Radius of effective aperture

$$h = 75/(2 \times 1{\cdot}25)$$

$$K_2 = 0{\cdot}85$$

$$A'^2 = 30^2/b^2$$

(*a*) Image scale $\beta = 1:1$, distance between lens and film $b = 2f = 150$ mm.

$$\eta_1 = \frac{0{\cdot}6 \,.\, 0{\cdot}85 \,.\, 30^2}{150^2} = 0{\cdot}002$$

(*b*) Image scale $\beta = 1:5$ (reduction), $b = 6/5$

$$f = 90 \text{ mm.}$$

$$\eta_1 = \frac{0{\cdot}6 \,.\, 0{\cdot}85 \,.\, 30^2}{90^2} = 0{\cdot}056$$

By using the value given for N in screen contact photography the values given in Table V for the efficiency of photography with camera and lens are obtained for the last lens.

TABLE V

EFFICIENCY OF LUMINOUS SCREEN PHOTOGRAPHY WITH LENS (EXTERNAL PHOTOGRAPHY)

Emulsion	$N \,.\, 10^{-9}$ (Energy Quanta per cm.^{2})	$\eta\left(= 10^5 \,.\, \frac{\eta_1}{N}\right)10^6$ Astro. Objective (R.K.)	
		$\beta=1:1$	$\beta=1:5$
Agfa isochromatic film . . .	190	0·010	0·029
Silver bromide paper (Oszillox) . .	83	0·024	0·068

Except for N, therefore, η is to a great extent dependent on the aperture of the optical system which is nearest the image, and by means of which reduction or enlargement at the same time takes place. In photography at the front side of the luminous screen, the efficiency in general becomes somewhat greater since absorption losses in the luminous substance are less. The advantage thus obtained is, however, partly offset by the fact that recording in this case takes place over a smaller angle than 90° to the tracing surface.

TABLE VI

COMPARISON OF VARIOUS METHODS OF TRACING WITH CATHODE-RAY OSCILLOGRAPH

(At $V = 70$ kV.)

Method of Recording	Emulsion	Efficiency $\eta = 10^5 \frac{\eta_1}{N} 10^6$	Maximum Tracing Velocity $v_{s\,max} = 400 \frac{i_s V}{d_s} \cdot \eta$ for $i_s = 1\mu a.$ $V = 70$ kv. $d_s = 0{\cdot}1$ cm. km. per Sec.
Electron ray photography in high vacuum . . . (Internal photography)	Agfa positive film	2·4	670
	Agfa X-ray film	7·9	2 200
Electron ray photography through Lenard window (External photography)	Silver bromide paper (Oszillox)	1·9	530
Luminous screen photography . (External photography)	Silver bromide paper (Oszillox)	0·72	200
Luminous screen photography with lens (External photography)	Silver bromide paper (Oszillox)	0·07	21

For the purpose of a quantitative comparison, the efficiencies of the four methods of tracing, already described, are set out in Table VI at an anode voltage of 70 kV. with a tracing current

i_s of 1 μA. and an electron spot of diameter $d_s = 0{\cdot}1$ cm. calculated at maximum tracing velocities. For if

$$\eta_1/N = 10^{-5} . \eta. \qquad (73)$$

is substituted in equation (56), then

$$v_{s\ max} = 400 . (i_s/d_s) . V_b . \eta \text{ km. per sec.} \qquad (74)$$

According to Table VI, internal photography gives the greatest efficiency, whilst the other methods of tracing come in the following order: electron window, luminous screen contact photography, and photography with camera lens. It is interesting to observe that the method of recording with camera lens is not as far behind the other methods of tracing as might be expected from the fact that a lens can only cope with a small percentage of the total luminous stream. A more precise determination of the efficiency of methods of recording has been carried out by von Borries.[(60)] The way in which the efficiency depends on the anode voltage V_b is of importance in the selection of a suitable method of tracing an oscillogram. Assuming that the electron density in the fluorescent spot is constant, it is to be expected that in the case of electron ray photography, the efficiency will vary with the depth of penetration of the electrons into the silver bromide emulsion, i.e. in accordance with V_b over a range which is limited in the one direction by the thickness of the emulsion, and in the other (at very low values of N) by the diameter of a grain of silver bromide. With equal energy density, therefore, and within the same limits, the efficiency is probably directly proportional to the exciting voltage V_b. In contrast to this, it is to be expected that the efficiency of luminous screen photography for voltages between 0·4 and 80 kV. will show a much lower variation with voltage than in the case of electron ray photography. The depth of penetration of the electrons in the luminous surface appears, in this case, to be less effective than in electron photography, probably because the luminous centres (metallic atoms) are smaller and more closely packed together than the silver bromide grains in the emulsion. Accordingly, in the case of luminous screen photography, as distinct from electron ray photography, there will be, with decreasing exciting voltage ($<$ 80 kV.) for the same load at the electron focus, a constant or perhaps increasing proportion of the electron radiation converted into light rays and capable of penetrating the silver bromide emulsion. For this reason, the efficiency of luminous

screen photography will increase relative to electron ray photography as the exciting voltage decreases.

The fact that luminous screen photography is more efficient than electron ray photography at exciting voltages of less than 5 or 10 kV. has already been proved qualitatively by Sommerfeld.[61]

Consideration of the relative efficiencies of the various methods of tracing at different anode voltages indicate the most suitable ones for use with low voltage cathode-ray tubes. The construction and mode of operation in this instance determine the method of tracing to be adopted. Internal recording, as in the case of high-vacuum tubes, need not be considered at all since the low-voltage cathode-ray tube is a closed glass unit sealed off at the pump and the use of internal mechanism is not possible. Neither can the use of electron ray photography be considered since the electron window in its present state of development is not sufficiently robust to guarantee operation over long periods without trouble. The replacement of a damaged Lenard window means the remaking of the whole tube. Screen contact photography and photography with camera lens alone remain for dealing with low-voltage cathode-ray tubes. For anode voltages between 500 and 4 000, however, both the last-named methods of tracing as described above are much better than electron ray photography, so that constructional features and operating conditions for the process of tracing agree on this point. Though the two methods first mentioned are unsuitable for low-tension oscillographs, a comprehensive treatment seems desirable as conditions change in the course of time, and oscillographs with higher anode voltages may come into use for purposes involving the use of small currents. Screen contact photography is at a considerable disadvantage, since the glass bowl of the tube which forms the fluorescent screen cannot, for constructional reasons, be made as thin as the supported screen contact window of the high-tension oscillograph. For the same reasons the bowl of the bulb must be curved. The efficiency of screen contact photography falls, therefore, to about one-fifth or one-sixth of that attainable with high-tension oscillographs.

The superiority of screen contact photography over photography with camera lens is not so great, therefore, in the case of low-voltage cathode-ray tubes as for high-tension oscillographs (about 2 : 1).

Whether screen contact photography or photography with camera lens should be used for low-current cathode-ray tubes depends on the nature of the oscillogram to be traced, the sharpness required, and consequently on the means available for obtaining efficient optical systems.

In practice there are three types of oscillography: the recording of stationary figures in periodic processes, tracing single determinate or indeterminate processes with electrical time deflection—both kinds of tracing resulting in a surface-like oscillogram on the luminous screen—and the third type of

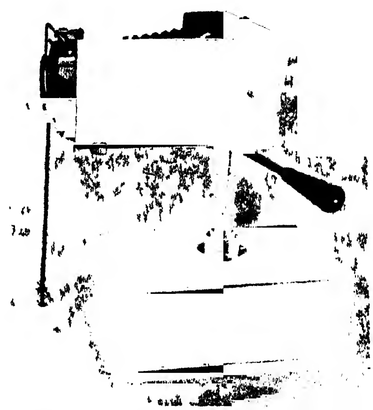


FIG. 262 EXTERNAL PHOTOGRAPHY WITH ORDINARY APPARATUS

tracing, i.e. oscillography with mechanical time deflection in which the cathode ray is merely influenced by the process to be traced and a deflection proportional to the work amplitude appears on the screen.

In tracing stationary figures, the efficiency is of little importance since the oscillograms are obtained by repeated re-tracing on the luminous screen. The efficiency need only be considered and pushed to its maximum value when short exposures become necessary as a result of poor synchronization of the process to be traced. In practice, photography with a camera lens is almost always employed for tracing stationary figures, although the use of luminous screen contact photography is itself possible in principle. Fig. 262 shows a standard camera for this purpose.

Tracing of non-recurrent phenomena is possible in principle with either camera lens or by screen contact photography. With

low-voltage cathode-ray tubes, photography with camera lens is the most useful for tracing processes with mechanical time deflection which require only one pair of plates in the oscillograph. In this case, either the entire camera can be moved relative to the luminous screen with time velocity as constant as possible, so displacing the image of the fluorescent spot to various points of the photographic sensitive material corresponding to the time co-ordinate of the process, or with a fixed camera, the light sensitive material is moved over the image plane in the camera, and in the same way an oscillogram of the process appears as a function of the time. Table VII (p. 309) gives a nomogram showing the maximum tracing velocity on the screen relative to the anode voltage and ray current for two sizes of spot diameter. From this the maximum tracing velocity under any practical conditions may be read off directly.

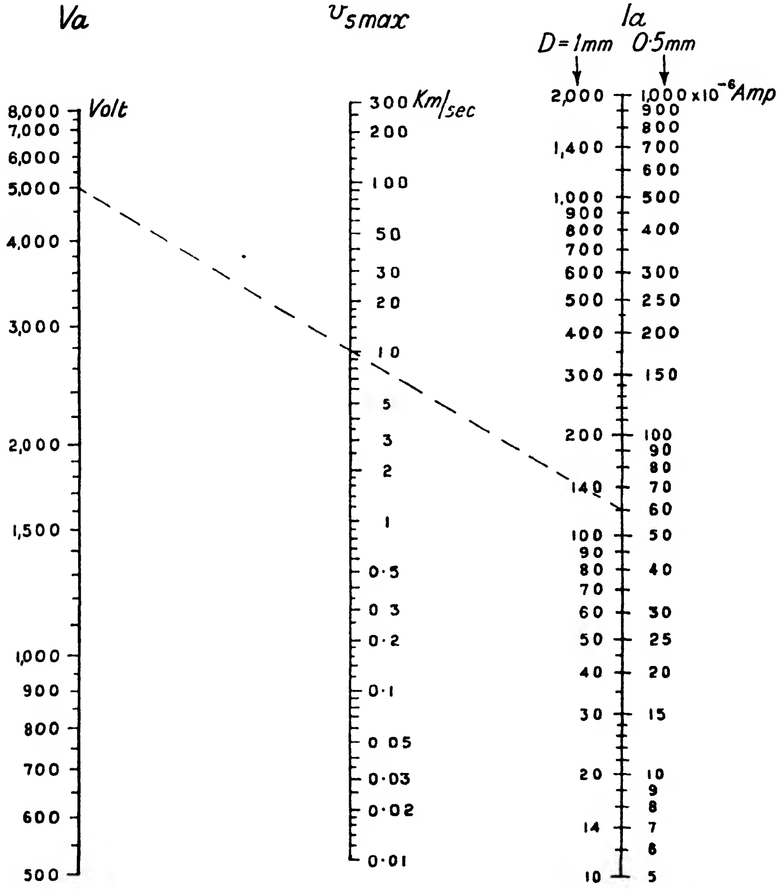
In the previous section the methods of tracing possible in principle with cathode-ray tubes have been mentioned, and their suitability for certain oscillographic processes has been discussed quantitatively and qualitatively. In the following section we shall discuss those points which require particular consideration in low current tubes in order to secure on the one hand the best results from photographic recording, i.e. the tracing of the high electron ray velocities, and on the other hand to carry out the recording of medium ray velocities as expeditiously as possible.

2. **Adjustment for High Ray Output.** As has already been seen from efficiency considerations, the oscillograph tube must first be adjusted so that the greatest possible brilliancy of the spot is produced. As already stated, the brightness depends on the velocity and the number of electrons striking the luminous screen; in other words, on the anode voltage and ray current at the screen end of the tube. In addition, the efficiency depends on the energy intensity in the fluorescent spot, i.e. on the diameter of the spot for a given ray current. The magnitude of the electron current can be varied by negative bias at the brightness control electrode. As the diameter of the fluorescent spot changes over the voltage range under discussion with a specified bias upwards, the magnitude of the anode current necessary for operation is practically determined by the value of the current which flows at optimum concentration of the spot. In practical low-voltage cathode-ray tubes this value of current, i.e. about 0·05 mA., is almost independent of

TABLE VII

Tracing Velocity Nomogram

Relation between the Screen Tracing velocity $v_{s\,max}$ the anode potential V_a and the ray current I_a for spot diameters D = 0·5 and 1 mm.



Aperture of the lens	$d/f = 1{:}2$
Absorption coefficient	$a = 0{\cdot}7$
Photograph. screen efficiency (with V_a = 5 000 volts and using calcium or cadmium tungstate) . .	η_p = 3HK/watt
Photograph. sensitivity (e.g. Agfa-Isopan-Super-Special Miniature film)	$\beta = \frac{18}{10}$ Din° = 2
Reduction ratio	$r = 1{:}4$
Blackening obtained	$s = 0{\cdot}1$

$$v_{s\,max} = \frac{d^2}{f^2} \cdot a \cdot \frac{V_a \cdot I_a}{D} \cdot \eta_p \cdot 10^{\beta} \cdot \frac{1}{2(r+1)^2}$$

the anode voltage. With the other determining factor—the anode voltage—on the other hand, a larger variation is possible. For example, suppose suitable preliminary amplifiers are available so that the drop in sensitivity at high voltages may be left out of consideration, the highest possible anode voltages naturally will be used. In gas-filled tubes, however, the anode voltage must not be increased too much. A limit is set, especially in the older types, by the voltage at which a glow discharge occurs inside the tube. If the tube is worked near the

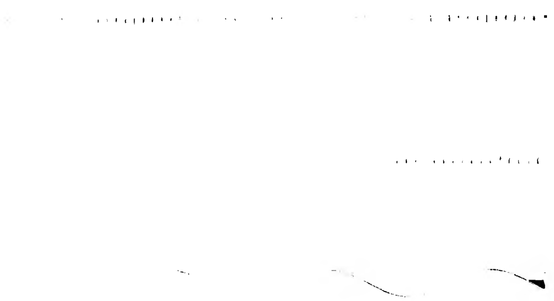


FIG. 263. OSCILLOGRAM OF AN OSCILLATION OF 4 000 CYCLES
(Ray output about 0·25 watts)

highest permissible voltage, then the current limiting resistance discussed in the section on mains equipment must be provided. The maximum voltage with older types of gas-filled cathode-ray tubes is about 4 500 volts, but the striking voltage may vary a little. It is preferable, therefore, not to work at voltages much in excess of 3 000. Here it may be pointed out that a discharge always occurs between Wehnelt cylinder and anode as long as the Wehnelt cylinder is at a negative potential with respect to the cathode, and is therefore the most negative point of the electrode system. This is important in so far as the oxide deposits are damaged by such discharges between cathode and anode. A further disadvantage of using voltages over 4 000 is that with the normal gas-filling the effect of gas-focusing becomes less and the ray becomes diffused (see above). The conditions which exist in modern arrangements with lower gas pressure are somewhat more satisfactory, inasmuch as

there is less tendency for a glow discharge to pass and less reduction in sharpness of the spot. Using an anode voltage of 3 000, the maximum tracing velocity which is attainable for photography with a camera lens using a suitable optical system (see below) is about 1 km. per sec. An oscillogram of an oscillation of frequency 4 000 traced at this speed is shown in Fig. 263, which was taken with an effective ray output of 0·25 watts. Indeed, by using modern tubes with high vacuum, or under favourable conditions with gas-filled tubes, tracing speeds of over 10 km. per sec. can be attained. An approximate idea of the influence of the anode voltage on the maximum tracing velocity is shown by the fact that, within the range under investigation, a reduction of anode voltage by one-half necessitates an optical system of almost twice the diameter for the same velocity of tracing. The efficiency of the oscillograph is influenced by the type of fluorescent screen as well as by the electrical constants. Further details of fluorescent screens are to be found in Chapter I, pages 126 to 144. There it was shown what an extraordinary difference exists between various screens both in respect of efficiency as well as spectral response. The selection of the most satisfactory photographic material is closely related to the spectral response of the screen.

3. **The Light-sensitive Material.** The previous sections have already indicated the importance of the choice of suitable photographic material in securing good performance from the oscillograph. In selecting the light sensitive material it should be ascertained first from the spectral curve whether the screen gives off mainly blue radiation (fluorescent materials 12 and 13 in table given in Chapter I, page 128), or if the peak intensity lies in the green or yellow portion (screens Nos. 2, 11, and 15). With the first spectral distribution it is unnecessary to employ panchromatic material for the photographic record, for in practice sensitivity only to the blue and ultra-violet is of importance. But experience with various kinds of plates and films has shown that panchromatic material, even in the blue range generally, has excellent sensitivity. Fig. 264 shows the difference in registration from the same treatment with different materials. In Fig. 264 (*a*) an almost imperceptible image is given. The photograph was taken with the Hauff ultra-rapid plate (21° Scheiner). The ortho-Elur plate (22° Scheiner) shows considerably greater photo-chemical effect (Fig. 264 (*b*)), while the oscillogram really becomes clearly

visible with the Lumière Opta plate (24° Scheiner), which has an extraordinarily steep gradation curve in the initial range. It will be observed that the somewhat arbitrary Scheiner scale provides a good basis for the conditions under review. Excellent results were obtained by the more sensitive types of Agfa Isochrom plates. The three photographs of Fig. 264 were taken at the same very low brightness of the fluorescent spot in order to distinguish differences in the range of low intensity illumination. These are important in practice, since with higher luminous intensity the action on the photographic material is always adequate.

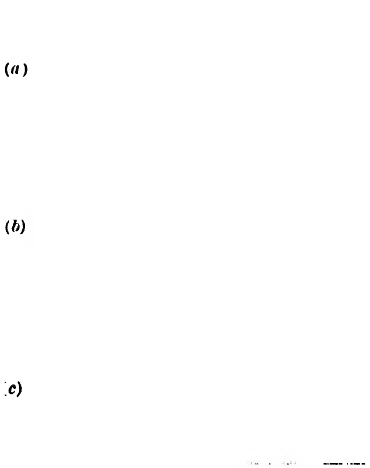


FIG. 264. DIFFERENCES IN TRACING FOR VARIOUS FILMS

In the case of the new screens with extremely high luminous efficiency to long-wave radiation, it is even more important than in the case of screens with a predominant blue radiation to select the most suitable kinds of plates. An example of the way in which the choice of plate affects the oscillogram is shown in Fig. 265. The upper oscillogram was taken with a normal highly sensitive, but not otherwise specially treated, commercial emulsion in which sensitivity to blue was known to be prominent. The lower oscillogram was obtained with a very good, highly sensitive panchromatic emulsion. In addition, corresponding halves of each oscillogram were traced with different screen materials, the upper half with screen No. 2 and the lower with an ordinary calcium tungstate screen. It can be seen that the highest tracing speed is attained with the modern screen No. 2 and panchromatic plate, but that with a plate sensitive only to blue the tracing speed is much lower than with a calcium tungstate screen. Once the commercial grade of plate which is particularly suitable for the fluorescent screen in question has been found, further presensitizing is quite unnecessary.

4. **Screen Contact Photography.** Screen contact photography as already stated is equally suitable for tracing stationary

figures and single non-recurrent phenomena. As, however, the intervening glass wall of the bulb causes the sweep of the oscillogram to spread out, screen contact photography will in general be limited to the tracing of single processes of high velocity which require high efficiency, since stationary figures

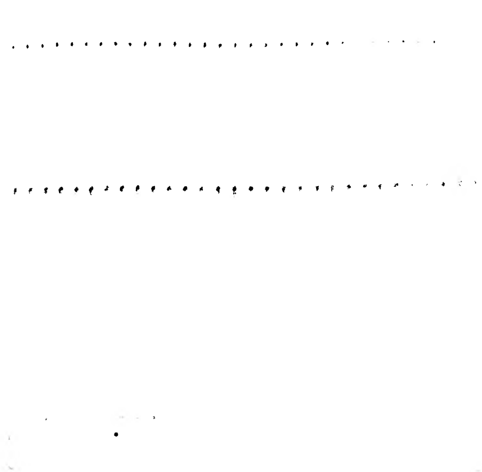


FIG. 265. THE EFFECT OF THE COLOUR OF THE SCREEN AND PHOTOGRAPHIC MATERIAL ON THE SPEED OF TRACING

can be photographed better with the camera lens. Screen contact photography has the economic advantage of not requiring any special photographic equipment. The photographic material in the simplest case is merely pressed by hand against the bowl of the bulb. One disadvantage of the method is that it is essential to darken the whole chamber in which the oscillograph is placed. This difficulty can be overcome by using special enclosures. In order to ensure that the photographic material may be firm against the bowl of the bulb, such boxes

need some complicated contrivance for pressing the material against the bulb, and the advantage of such an arrangement does not appear to warrant the cost involved.

The round bowl of the oscillograph tube also restricts the photographic material which can be used. In order that the

FIG. 266 CONTACT PHOTOGRAPHY OF A STATIONARY FIGURE ON NORMAL GASLIGHT PAPER
(Ray output 0·05 watt, exposure 4 sec.)

oscillogram shall be as sharp as possible, flexible material such as films or bromide paper must be used, and only small parts of the screen employed. Gaslight papers of low sensitivity are good enough for tracing stationary figures, whereas highly sensitive bromide paper is necessary for tracing single high-speed

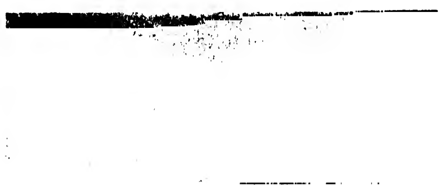


FIG 267. SCREEN CONTACT OSCILLOGRAM WITH 1 MM. THICKNESS OF GLASS WALLS AND A MEAN TRACING SPEED OF 2·5 M./SEC.
(Ray output 0·15 watt, Oszillox Paper)

phenomena. It should be noted that ordinary commercial papers are nearly always sensitive only in the blue region of the spectrum. Fig. 266 shows a contact oscillogram of a stationary figure at an effective ray output of 0·05 watts and an exposure time of 4 sec., taken on normal sensitivity gaslight paper. The oscillogram of Fig. 267 was recorded on Oszillox paper from a single trace.

5. **Photography with Camera and Lens.** The tracing of all periodically recurrent processes. i.e. stationary figures, as also

the tracing of single low frequency or even medium frequency processes, is possible with a camera lens. The procedure in this method is relatively simple, and in many cases can be carried out with apparatus already available for other purposes. Here, the kinetic energy of the electrons, which is converted into luminous energy on the fluorescent screen, is used for tracing, a simple optical system being interposed. The factors relating to freedom from distortion and adequate exposure of

FIG. 268 ARRANGEMENT FOR PHOTOGRAPHING OSCILLOGRAMS ON THE INSIDE SURFACE OF THE SCREEN WITH CAMERA ON A SIMPLE SWIVEL SUPPORT

the photographic material come within the realm of the optics of photography The recording camera must, in construction as well as its optical system, be adaptable to the process to be traced. Before details of the complete photographic tracing apparatus are considered, let us discuss first which side of the screen—inside or outside (see Fig. 268)—it is best to photograph. The answer to the question, which of the two methods of photographing is the more advantageous, depends on the construction of the fluorescent screen. Generally, the screen is applied so thinly that the same approximate brightness exists on either side, in which case the screen is transparent. With the evenly distributed screens of modern tubes, photography from the outside is more practicable and is generally employed. The total brightness which is distributed over both

sides is somewhat less than the brightness on denser fluorescent screens, because with these the whole of the electron stream is used in exciting fluorescence and no portion of it impinges on inactive surfaces (see section on fluorescent screens). With denser screens the greater part of the luminosity produced is directed inwards, in which case the position of the photographic equipment shown in Fig. 268 is advantageous.

Cathode-ray tubes are sometimes provided with denser fluorescent screens on account of their greater luminous efficiency. The density, however, is then chosen so that in the case of stationary figures where the exposure time is not important, photography from the outside is possible. This is important with two-dimensional stationary figures as the geometrical distortion is least with external photography. At first it would appear that, in oscillography with the arrangement shown in Fig. 268, considerable distortion would occur, first from oblique tracing. and secondly from refraction by the glass. In practice this is not so, as long as extremely large amplitudes do not occur. As the ray path is very nearly at the same distance from the camera along the whole of its length, oblique photography is not objectionable in spite of the fact that the aperture is large enough to allow the spot to get out of focus. Nevertheless, the camera or film container should be brought up to the tube as close as possible unless the need for moving the apparatus is an objection. Fig. 269 shows two positions for the camera. Usually operations will take place from position 1. However, in order to show that even in the more unfavourable position 2, particularly in respect of distortion resulting from refraction by the glass, quite satisfactory results can be obtained, an oscillogram which was taken in such a position is shown in Fig. 270. By comparison, this record shows very good agreement with one obtained by a rotary mirror outside the fluorescent screen. These results show that it is desirable to make photographic records of high frequencies from the

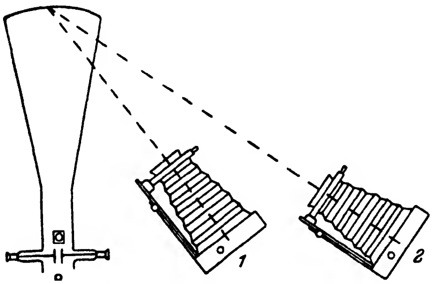


FIG. 269. SUITABLE AND UNSUITABLE POSITIONS OF THE SUPPORT

inside surface. In all other cases, photography from the outside of the screen is advisable.

It should be noted that photography from the inside of the fluorescent screen is only possible when the camera or light sensitive material is movable, but not when electrical time deflection (see below) is used, as in this case a surface has to be photographed and on account of the short depth of focus of the wide aperture lens, an out-of-focus image results. This limitation does not, of course, occur with tubes having inclined screens.

(A) APPARATUS FOR FORMING THE IMAGE. The optical system of the camera employed must in practice be selected to be of

FIG. 270. OSCILLOGRAM OF A SINE WAVE VOLTAGE PHOTOGRAPHED THROUGH THE SIDE OF THE TUBE

sufficient power, so that with a given brilliancy of the fluorescent spot and sensitivity of the photographic material, sufficient exposure will be obtained at the ray velocity of the process to be investigated, i.e. the lower curved portions of the gradation curve will be avoided.

Larger aperture lenses should be chosen for higher ray velocities. If a highly sensitive material is available, lenses of about $f/3{\cdot}5$ which are quite usual in modern photographic equipment, are sufficient for tracing oscillations of about 2 000 cyc. with a length of stroke of 5 cm. on the screen, and with the ray currents and anode voltages of modern tubes. If it is desired to register higher frequencies or to work with greater precision, larger aperture lenses are advisable. Such lenses for plate as well as film cameras are obtainable from any photographic dealers. With any particular lens, the sharpness of the tracing must always be such that the energy density in the spot on the photographic material does not change appreciably. Less than the maximum sharpness in the tracing can only be tolerated when the problem in hand can be satisfactorily treated by a less sharply defined oscillogram. In many problems the use of special optical systems to secure extremely sharp oscillograms is an unnecessary expense.

As the fluorescent screens generally show a particularly high luminosity to a certain portion of the spectrum, it is possible to dispense with chromatic correction of the objective when the spectral sensitivity of the light sensitive material is the same as the colour of the fluorescent screen. It is sufficient in such a case for the lens to be corrected only for spherical aberration. In this way it is possible to secure lenses which are cheap and yet have high power and long focal length. A special objective for cathode-ray tubes developed along these lines by the Astro Co. of Berlin-Neukolln is shown in Fig. 271. The objective on the left is fitted with an adjustable diaphragm. This lens, with extremely low glass absorption, has a geometrical aperture ratio of 1 : 1 with a focal length of 5·0 cm. The same lens system is constructed with a focal length of 12 cm. for the projection of screen images on fairly large surfaces.

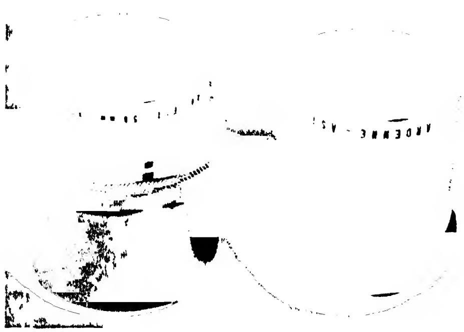


Fig. 271. Special Optical System of Astro Co. for Cathode-ray Oscillographs
(Aperture ratio 1 : 1, focal length 50 cm.)

Bearing in mind the nature of the dispersion curve of ordinary optical glass, the use of objectives chromatically uncorrected is to be recommended only in conjunction with screens having small blue radiation (e.g. No. 2).

To make full use of the much greater sharpness of tracing possible with modern tubes, first-class objectives, chromatically corrected, are usually essential. The oscillogram of Fig. 272 shows the sharpness of tracing of modern tubes and that required of the photographic lens. With the more efficient apparatus discussed further on, adequately corrected optical systems with powers of 1 : 1·4 are used. Special mention must be made of the fact that the maximum tracing velocity which can be recorded is greater with a lens having a sharp focus and lower power than with one having an ill-defined focus and higher power, since for photographic recording the intensity of illumination at the spot, and not the total

amount of light, is the important factor. If it is optional whether cemented or uncemented lenses of equal efficiency are to be used, the former are preferable, since the loss of light by reflection at the glass/air surface is considerable. As is well known, the light lost at each boundary surface amounts to about 5 per cent and therefore is sufficient, particularly with uncemented double anastigmatic lenses, to make the effective aperture much less than the geometrical aperture.

(B) PHOTOGRAPHIC ARRANGEMENT. The choice of the

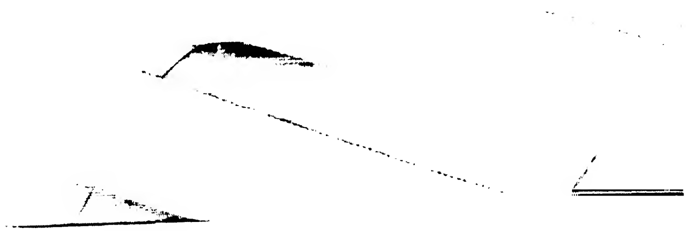


FIG. 272. OSCILLOGRAM OF A TELEVISION RASTER SHOWING THE EXTREME SHARPNESS IN TRACING WITH A MODERN HIGH-VOLTAGE TUBE

photographic equipment depends on the type of oscillograms to be photographed, according to whether these are of short or long duration.

(i) *Photography of Oscillograms of Short Duration with Plates and Rotating Drum Camera.* If merely a short time section from some periodic or non-periodic oscillation is to be recorded, then plate equipment, perhaps with a small-sized picture, is sufficient. If a special camera is not available, the existing camera must be arranged at a suitable height so that it can be rotated. Such a camera stand is shown in Figs. 262 and 268. The lever shown facilitates rotation of the camera and so secures the desired time interval. If the stand is accurately constructed it is easy to bring the zero line also into the oscillogram by operating the tube with alternating voltage, giving it one rotation, and without alternating voltage after a second rotation. The possibility of doing this is very useful for the investigation of rectifiers. In order to economize in plates

it is desirable to photograph several oscillograms successively on one plate. To do this, it is only necessary to alter the height of the lens by means of the adjustment provided in most cameras for this purpose. By examining the ground glass screen and estimating the maximum amplitude which occurs, it is easy to prevent the curves overlapping.

Instead of producing the time deflection by moving the entire camera relative to the fluorescent spot, the photographic material may be moved relative to the fluorescent spot and lens system even when the latter is fixed. Fig. 273 shows such

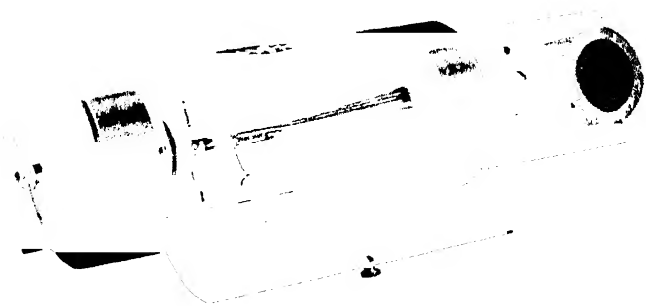


FIG. 273. PHOTOGRAPHIC ARRANGEMENT WITH INSTANTANEOUS SHUTTER AND RECORDING DRUM

a photographic arrangement by Zeiss-Ikon, the cathode-ray tube, the instantaneous shutter opening, and a rotating drum being built up into one unit.

Another camera in which the light sensitive material is also placed on a recording drum, is shown in Fig. 274. In this design a drum made of light metal with a relatively large circumference is used, and the film or paper strips stretched over it to a length exceeding 1 metre. The advantage of this arrangement is the great length of the oscillogram, and the possibility of attaining very high circumferential velocities with a motor-driven drum. In order that exposure shall take place only once during a single rotation of the drum, it is necessary for the shutter of the lens aperture to be open for a time equal to that of one rotation of the drum.

To be able to determine the necessary exposure at any time, a speedometer is connected to the axis of rotation of the drum as in the arrangement shown in Fig. 274, thus showing the

FIG. 274. CAMERA WITH LARGE CIRCUMFERENCE RECORDING DRUM FOR VERY HIGH SPEEDS
(Institute A. Widmaier T. H., Stuttgart)

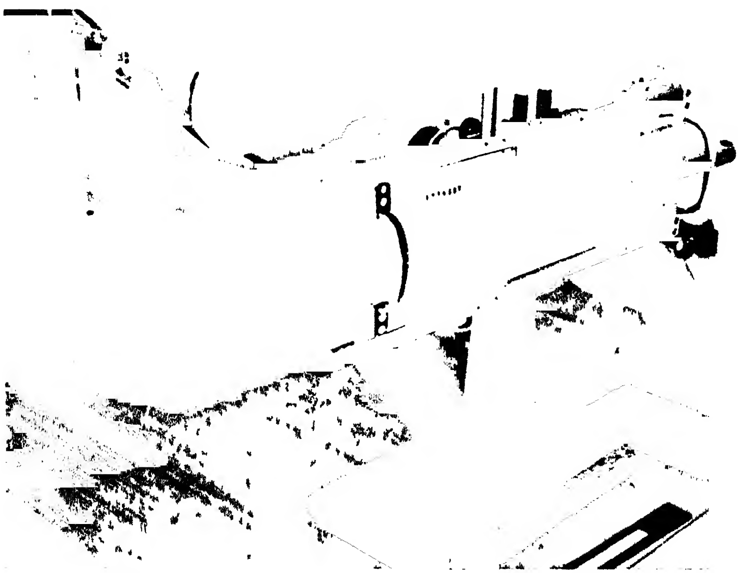


FIG. 275. REAR VIEW OF THE AUTHOR'S OSCILLOGRAPH CAMERA

necessary exposure time of the aperture when required. These additions make the apparatus expensive. A further disadvantage of the older forms of construction is that the light-sensitive material must be loaded in a darkened room and the loading and unloading is much more troublesome than, for instance, the loading of plates in boxes. These disadvantages are avoided in the oscillograph camera shown in Fig. 275. The deflection of the spot on the screen caused by the voltage to be oscillographed is in this case projected on a narrow slit by the specially wide aperture lens discussed above. The width of the slit should be just enough to enable the optical image of the sweep to pass through completely. The slit is effective by reason of the fact that to a great extent only light from the zone over which the spot is passing is recorded. The exclusion of extraneous light (e.g. halos) results in a particularly clear oscillogram, and makes recording in undarkened surroundings possible in spite of the high-power lens. The motion of the light-sensitive material in front of the slit is carried out by the dark-slide which holds it, and which is moved past the slit in guides under the tension of a spring. The velocity of the movement can be varied within wide limits by adjusting the tension of the spring. The arrangement is designed so that the slide attains its full velocity before the light-sensitive material reaches the slit and the slide then moves past the slit with constant velocity, being pulled up shortly after passing. If the friction between the slide and its guides is very small, uniform motion during its passage past the slit is secured. The regularity of the motion can also be seen from the oscillogram shown. The maximum velocity of the light-sensitive material with this arrangement is about 4-5 m. per sec. The velocity of the movement past the slit is controlled by the light from an a.c. mains-operated neon lamp, which passes through the slit in a small beam either below or above the image of the fluorescent stroke (see Chapter II, pp. 330 to 336).

With the lens system employed and a reduction of at least 1 : 3 to 1 : 4 necessary to secure adequate intensity of illumination, the maximum width of the oscillogram, including the adjacent strip (a few millimetres wide for the time marking), amounts to about 3 cm.

Raising the box slide which is seen in Fig. 276 makes it possible with the 9 cm. × 12 cm. size stock used to put three oscillograms under one another on the same plate. Orientation

of the camera and adjustment of the lens is carried out by means of the ground glass screen which can be introduced behind the slit at the approximate level of the light-sensitive material. The time of exposure which the camera has to record amounts to $\frac{1}{5}$–$\frac{1}{50}$ sec., according to the tension of the spring. If non-periodic processes of short duration are to be oscillographed, it is essential that the event must take place

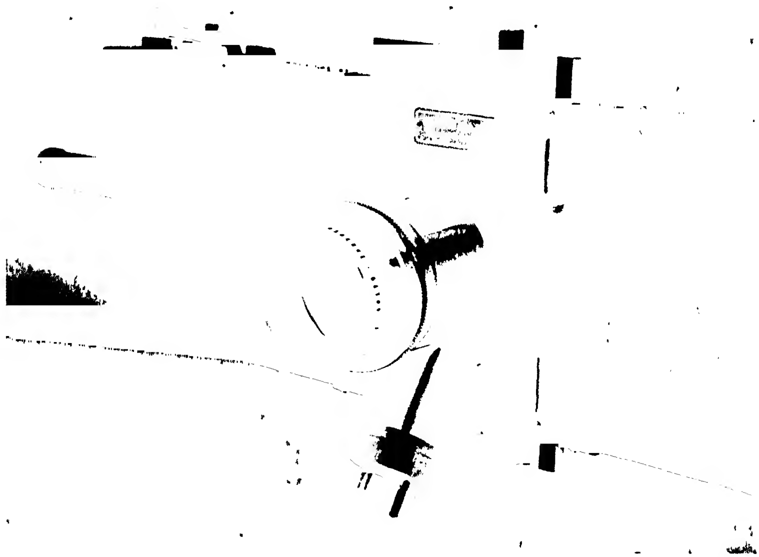


FIG. 276. FRONT VIEW OF THE CAMERA FOR PHOTOGRAPHING SHORT TIME OSCILLOGRAMS, SHOWING CONTACT RELEASE, HOLDER FOR NEON LAMP GIVING TIME INDICATION, HEIGHT ADJUSTMENT, ETC.

in the short time interval mentioned during which the light-sensitive material is in front of the slit.

In order to arrange this with non-recurrent processes, the electrically-released lever is combined in its construction with the contact device shown on the left of Fig. 276, which makes contact simultaneously with, just before, or just after, release. In the equipment described ordinary tin boxes are used, so that the light-sensitive material can be fixed without adjusting, transporting the recording equipment, or making the space dark and simple operation and ability to reproduce the final adjustments of the optical system are

secured. Fig. 277 shows two oscillograms with the time scale marked on the same plate with the simple camera and optical system mentioned. The oscillogram shows excellent contrasts in spite of the fact that only the ordinary anode voltage, types of plates, and normal development were involved. For problems where analysis in more detail is necessary, the same construction of camera is used but with improved and chromatically corrected objectives—the latter being most important. Sometimes it is necessary for special purposes to

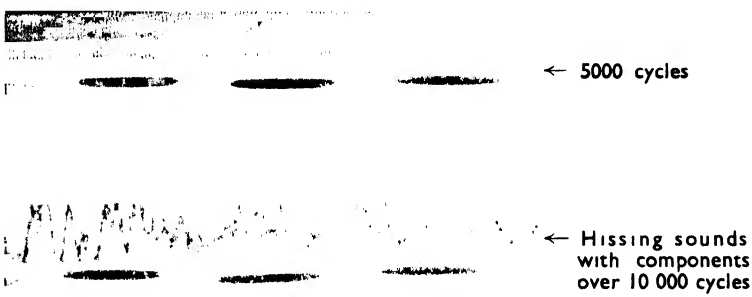


Fig. 277. Oscillogram and Time Scale obtained with the Camera of Fig 281 having a Simple Optical System

photograph several oscillograms not successively, but simultaneously on one and the same light-sensitive material. In such cases, either a special optical system or an ordinary one with longer focal length and particularly sharp focus for clearness in tracing, must be used for each oscillogram. Simultaneous photography of two or three oscillograms is carried out by arranging two or three tubes with small bulbs directly above one another, and the fluorescent sweeps resulting from deflection are then traced below each other.

(ii) *Photography of Long Period Oscillograms with Film Equipment.* Extremely long oscillograms may with advantage be recorded by means of a film camera. When ordinary film cameras are used for this special work, the Maltese cross must be removed in order to ensure a uniform motion of the film instead of the usual intermittent motion. The strain on the film and on the driving mechanism at a given velocity in

metres per second is very much reduced when the motion is uniform. Consequently, relatively high speeds (up to five m per sec.) are possible without any trouble. The camera is usually

FIG. 278. AN OLDER FORM OF HAND-DRIVEN FILM RECORDING EQUIPMENT WITH A WINDOW TO PERMIT OBSERVATION OF THE OSCILLATION IN THE ROTATING MIRROR

FIG. 279. SIMPLE FILM CAMERA WITH MOTOR DRIVE

driven electrically or by hand. Fig. 278 shows an arrangement of photographic equipment which is driven by hand, and which at the same time permits of observation in the rotating mirror the oscillation to be photographed, so that the desired portion of the oscillogram can therefore be selected. Generally, however, an electrical drive will be preferred to the ordinary mechanical drive by a belt so that a wide variation in speed can be secured without strain. Shunt motors with adjustable

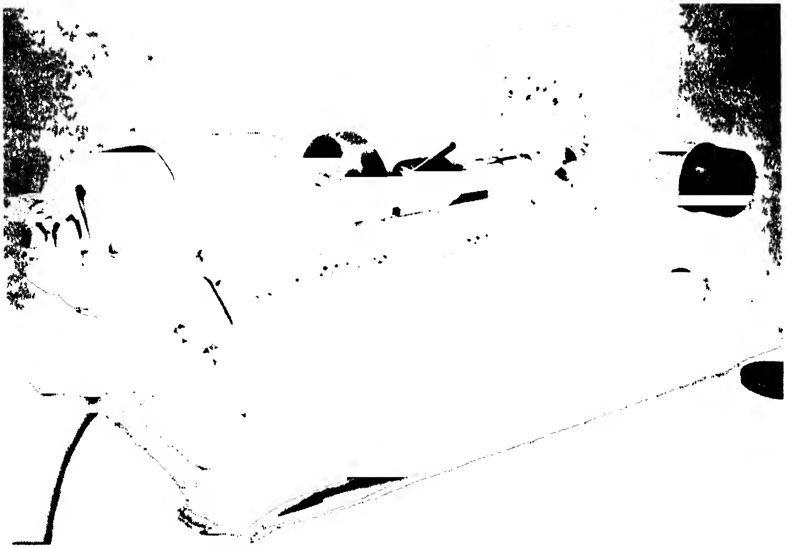


FIG. 280. RECORDING EQUIPMENT FOR FILM VELOCITIES BETWEEN 0·5 AND 20 M/SEC.

brushes are particularly suitable for this purpose. The power required is about one-sixth h.p.

An old type of camera with an electrical drive is shown in Fig. 279, and a more modern construction in Fig. 280. Storage drums for 30 to 60 metres of film are sufficient for the average length of oscillogram. A box which can be placed near to the camera and which accommodates about 30 metres of film is provided to receive the exposed film. This box is closed by a shutter, which at the same time acts as a knife and cuts off the exposed film, which can be taken out of the camera in daylight to be developed. In the latest form of construction a still more compact assembly than that shown in Fig. 280

is provided. By using special reduction gearing, and by regulating the drive, any film speed between 10 cm. and 25 m. per sec. can be obtained. In fact, for special problems, contrivances for registration up to 80 m. per sec. have been developed, and these, in conjunction with particularly high anode voltages and efficient tubes, enable recording of periods of 10^{-6} sec. to be carried out. In order to reduce film consumption, i.e. to bring the film up to the required speed in the shortest time, and also

Fig. 281 Coupling and Braking Arrangement for Reducing the Consumption of Film

to bring it to rest quickly, a special coupling and braking device is usually provided, particularly when the film speed is high. The principle of such a device is shown in Fig. 281. If the motor with its moving parts has reached the necessary speed of revolution, a slight pressure on the lever which brings the conical friction coupling into action, is sufficient to give the necessary speed to the film. Immediately the control is released, the brake is applied by the spring and the band of film brought to rest. The cost of the accessories mentioned becomes worth while, particularly when oscillograms of very rapid processes are to be made. If both film velocity and the process under examination are relatively slow, the friction of the film itself is a sufficient brake. In such a case only the coupling device needs to be provided. If a number of oscillograms are to be

photographed at different times, a time indication, such as the illuminated dial of a watch or something similar, should be photographed at the same time so as to make subsequent identification of the oscillograms possible.

VI. Slow Photographic Recording of Amplitudes

In the photographic recording discussed in the last section, the object was to record the exact outline of the whole oscillation. In a number of cases, however, slow photographic recording of the ray deflection amplitude without making individual oscillations visible. For example, in tracing the frequency characteristics of amplifiers, microphones, loudspeakers, etc., which involves recording values of amplitudes, i.e. in general concerning all problems where sudden amplitude fluctuations occur in the work circuit over a period of a few minutes. In order to show clearly the special advantages of recording amplitude values with cathode-ray tubes, we will discuss briefly the usual methods employed. In most cases, the amplitude values are measured by a series of points.

For this purpose integrating voltmeters (instruments showing the effective value) are used for the input and output alternating voltages. The points obtained are joined to form a continuous curve. If the amplitude curve has an involved outline with many fluctuations, a considerable number of points close together should be traced. The method in the presence of rapid fluctuations is very troublesome, easily produces errors of measurement, and finally cannot be used at all for variations which extend over a few seconds only. If the curve is made with a tracer, such as a pen, which makes an automatic record, the whole outline of the curve and the points of detail in it can only be registered by the instrument up to a point where its inertia introduces an appreciable error in the mean value.

The necessity of redrawing the curve in consequence of non-linear relation between the measured value and applied alternating voltage, the indeterminate errors in the indicator which result as a variation of the form-factor of the oscillation, and other disadvantages, would seem to make registration by this method unsuitable for some purposes.

The registration of amplitude values with cathode-ray tubes as distinct from the usual tracing methods mentioned, has several fundamental advantages.

The cathode-ray tube is not an integrating instrument; it

follows the outline of the output voltage without any lag. The voltage to be measured and the deflection of the ray are practically linearly related, so that the curve traced can nearly always be used without redrawing. Linearity results in a great simplification of ordinate calibration, which can generally be done by injecting a known voltage in the record either before or after making measurements. If the deflection of the ray in the cathode-ray tube is photographically recorded, it is possible to make deductions which would not be possible with the use of r.m.s. voltmeters. In the record traced by the cathode-ray tube, voltage harmonics are easily seen. During the process of recording, a more or less definite photographic impression is noticeable according to the velocity of the moving spot. For example, with a sinusoidal voltage, the points of reversal are sharply defined. If the second harmonic is very prominent, increased blackening appears near the zero zone, and so on. Deduction of the distortion factor from these measurements is sufficiently clear for most purposes. Furthermore, by this method of recording, asymmetry in the oscillation, which may be caused by asymmetry in the unit under investigation, can be recognized by the amplitudes being unequal on either side of the zero line. The ordinary method of recording would merely show a mean value instead of an unsymmetrical outline. Further, in recording values of amplitude with cathode-ray tubes, superimposed high frequency or hum voltages which are present with the voltage to be measured are recognizable with certainty. It is also possible, when recording amplitudes of modulated high-frequency voltages, to include the degree of modulation, since the zones in which the points of reversal of the sinusoidal voltage lie are shown.

Finally, another advantage which must not be underrated is that as a result of the absence of inertia in the recording device, the tracing can be very quickly completed, providing that no inertia in the measuring circuit has to be considered. An equipment for the slow recording of amplitude values is shown in Fig. 282. The equipment consists of a drum for the light sensitive paper driven by clockwork at a regular speed which can be altered at will. The time of revolution of the drum can be varied in two stages, and within these stages continuously, so that a range of time between one-half and six minutes is covered. The position of the drum at any time is shown by an indicator rotating in step with it. In

place of an indicator, a coupling can be used in the equipment shown for the purpose of providing a direct mechanical connexion with the time axis, for instance, to couple it to a governor or to the variable condenser of an audio-frequency oscillator.

Even without direct coupling, an abscissa scale suitably adjusted to the work circuit can be obtained in view of the uniformity of the drum rotation. As a rule, the time of revolution of the recording drum should be adjusted to be somewhat

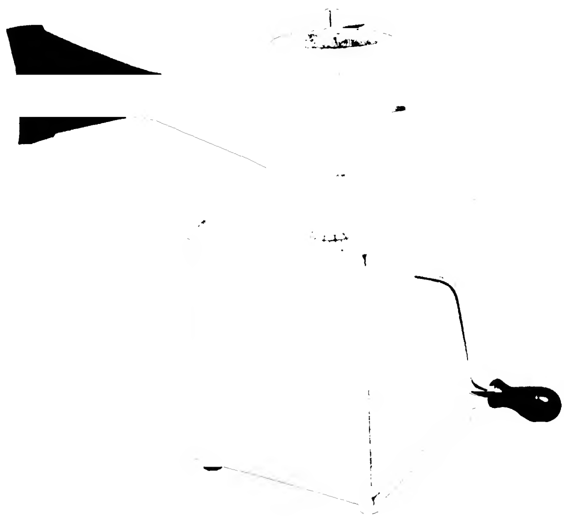


FIG. 282. EQUIPMENT FOR LOW SPEED RECORDING OF AMPLITUDE VARIATIONS

greater than the period of the process under examination. It is possible with this proviso to introduce the calibration voltage previously mentioned before or immediately after the finish of the tracing, and in this way obtain a time scale. If these time marks which limit the work circuit are insufficient, and it is required to add others, they can be obtained in a very simple way by disconnecting the measured voltage from the tube for a short time. The recording equipment shown is built so that it can be brought up directly to the fluorescent screen of the tube. The slit opening ensures that as little extraneous illumination as possible passes through the slit, so that recording can be carried out under conditions of ordinary

external illumination. In order to prevent the ingress of light, both before and after the actual recording, a shutter is provided in the equipment. The optical system through which the light beam passes is so arranged and designed that a sharp image of the fluorescent stroke appears on the surface of the

FIG. 283 RECORDED FREQUENCY CURVE OF A PICK-UP HAVING A LOW COEFFICIENT OF NON-LINEAR DISTORTION

paper if the screen is brought up to the opening. The power of the lens is chosen so that sufficient action takes place on the paper when ordinary material is used, operation taking place at 1,500 volts anode potential and at the rate of rotation mentioned. An on-and-off switch for the drum rotation, and

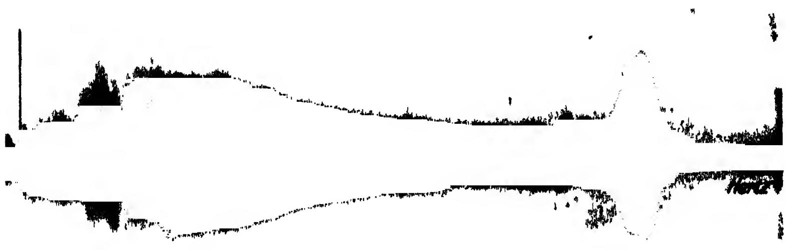


FIG. 284 RECORD SHOWING HIGH HARMONIC CONTENT PARTICULARLY IN THE RANGE ON THE LEFT

one which is independent of the velocity control, enables the rate of rotation once adjusted, to be maintained. Figs. 283, 284, and 285 show several records which indicate the typical peculiarities of the methods discussed. Fig. 283 is a photograph of an amplitude curve of a pick-up when the velocity amplitude is kept constant and the frequency varied. The

pick-up under investigation operates without amplitude distortion over almost the whole frequency range, since a complete record appears right up to the edges of the curve, and between the limits recorded there are no appreciable variations in density, i.e. the voltage recorded is very nearly sinusoidal. Fig. 284 shows another record in which a high harmonic content is present, especially in frequencies up to 200 cyc.; this also from a pick-up. The striations in the low-frequency range of the record can be reproduced entirely by repetition

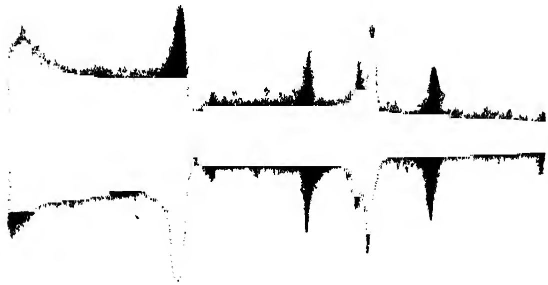


FIG. 285 FREQUENCY CURVE OF AN ALMOST COMPLETELY UNLOADED ELECTROMECHANICAL SYSTEM AND SHOWING SEVERAL POINTS OF RESONANCE

of the measurements, and are characteristic of the outline of the curve showing how the amplitude varies dynamically in the case of the instrument under test.

In this case it must be pointed out that with the higher definition in recording possible in modern tubes, the amplitude values and the striations are much more noticeable than they appear here. The record of Fig. 285 is also extremely instructive. This is the frequency characteristic of an unloaded, undamped loudspeaker system which shows a series of well-defined resonance points. It can be seen from the record that the sinusoidal shape of the voltage is only visible at the resonance points. Between the resonance points, the limits are not at all clearly defined. The oscillogram of the voltage characteristic in the intermediate range showed that at these points the voltage showed a strongly-defined third harmonic.

The examples shown should give sufficient indication of the suitability of slow photographic recording of amplitude values with the cathode-ray tube for certain problems of measurement.

VII. Simultaneous Recording of Time Scales

In the recording of non-periodic processes, simultaneous registration of time scales is of great importance for evaluating the curve. Time-marking is also necessary with periodic curves if there is no characteristic component in the oscillogram which can be recognized by its frequency. The time variable is registered automatically if the data of the time deflection are known exactly, i.e. the law which the time deflection obeys and the magnitudes involved. For example, in saw-tooth oscillations which have a linear rise, the time scale is completely recorded if the discharge frequency and length of the fluorescent stroke caused by it are known. A simple numerical example may give an idea of the time scale which can be attained with such oscillations, assuming the discharge frequency is known to be 20 000 cyc. The space covered by the cathode ray periodically due to the discharge voltage extends over a length of 15 cm. Then 1 mm. on the time abscissa of the fluorescent figure corresponds to 1/3 000 000 sec. Time-marking can be made in a similar way with discharge voltages having an exponential rise or fall or with sinusoidal voltages of known frequency. But in such cases the law involved must be taken into consideration.

The time scale in mechanical time deflections is also indicated in a simple manner if the velocity of the moving parts is definite and known. The case in which a synchronous motor drive controls the optical or electrical time deflection is a typical example. The most general method is that of electrical time deflection by saw-tooth voltages with linear rise or fall already discussed in detail above. Discharge voltages of precise and known frequency are relatively seldom available in the laboratory. On the other hand, sinusoidal voltages of known frequency, say from 50 or 500 cyc. supply, audio-frequency generators such as tuning forks, valves or quartz crystals, are usually available.

Synchronization of the discharge voltage with the sinusoidal voltage in accordance with one of the methods described above results in the formation of definite frequencies of discharge. From time to time tests should be made to check the frequency. When testing, it is only necessary to connect the sinusoidal voltage to the ordinate plates of the cathode-ray tubes for a short time, and count the number of curve traces visible. The

synchronization of discharge oscillations described above is therefore not only of importance in the formation of stationary figures in periodic phenomena, but also in the production of precise electrical time deflection generally. In all cases where time scale marking is not carried out by, or is not possible with, the device itself, it must be done by the assistance of accessories. The simplest way of getting a time indication in photographic recording or observation in a rotating mirror, is to photograph

FIG. 286. TIME SCALE RECORDING BY SIMULTANEOUS PHOTOGRAPHY OF A SMALL NEON LAMP FED FROM A.C. MAINS

simultaneously with the curve of the measured voltage, a neon lamp which is operated from a 50 cyc. lighting supply or other source of current of known frequency. At the same time the reflection of the neon lamp should take place as nearly as possible simultaneously with the motion of the spot, as otherwise errors will occur if the velocity of deflection is not constant. It is easiest to bring the neon lamp up to the path of the fluorescent stroke at the end of the bulb. Such an arrangement using a typical neon indicator lamp is shown in Fig. 286. The

time scale obtained with this arrangement is shown in Fig. 287. In order to obtain a clearly-defined time scale, it is advisable to use a small lamp or one which is partially obscured and

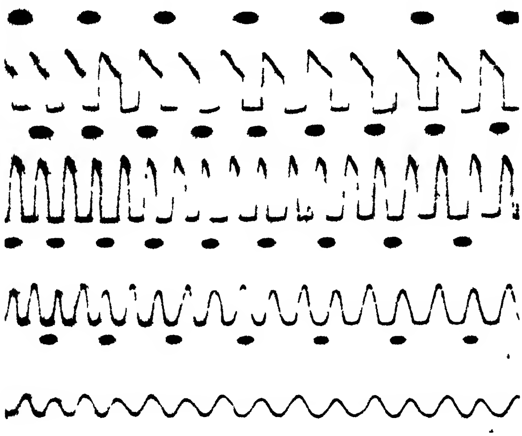


FIG. 287. TIME SCALE RECORDING BY A NEON LAMP FIXED EXTERNALLY AND OPERATED FROM 50 CYCLES MAINS

in which the striking and extinction voltages are not too widely separated, so that the lamp lights up only for a short time at the instant when the alternating voltage reaches its maxi-

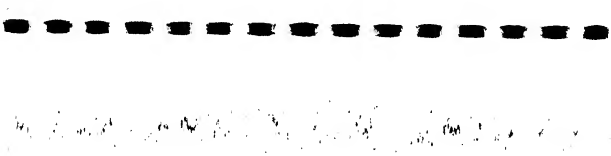


FIG. 288. TIME SCALE RECORDED BY A SLOT FIXED AT THE SIDE AND ILLUMINATED BY A NEON LAMP FED FROM A.C.

mum value. As the arrangement is above or below the fluorescent stroke, the curve itself is not affected. Fig. 287 indicates the time-marking from a neon lamp operated from a 50 cyc. lighting supply. The separation between the black dots represents

$\frac{1}{100}$ sec., since the obscuring of the lamp was arranged so that the light intensity remained the same in both positive and negative half-cycles. The design of the neon lamp for time-marking is less restricted if the marking is carried out with the assistance of a slit similar to that used with sound films which permits a band of light of fluctuating intensity to be recorded on the side of the film. In such cases, ordinary commercial neon

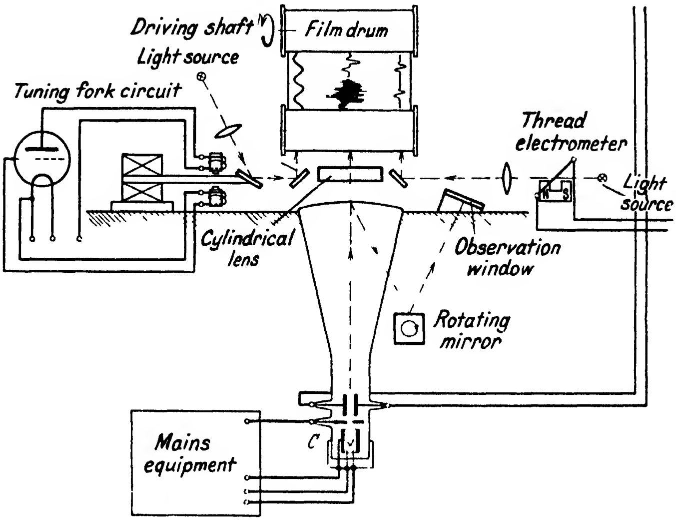


FIG. 289. ARRANGEMENT OF DRUM RECORDING FOR TRACING A SINUSOIDAL AND AN ADDITIONAL TIME SCALE SIMULTANEOUSLY

lamps used on lighting circuits can be employed. Time indications made in this way on a strip of film are shown in Fig. 288. If the time scale is to be recorded very accurately, the simple neon lamp method discussed is inadequate. It is necessary to work with a larger number of more sharply-defined marks. For instance, a slotted drum driven by a synchronous motor is used in conjunction with modern methods of recording, and this supplies 500 flashes of light of short duration per sec. which are suitable for time-marking. Another method of time-scale recording,[62] which is more accurate and which has been in use for a considerable time, consists in tracing a time scale next to the oscillation curve with the aid of an oscillating luminous spot. In this case it is possible to carry out optical reflection simultaneously with or separate from the curve. In the first

case the oscillating luminous spot must again be brought up to the fluorescent spot either by optical or mechanical means. An arrangement with separate optical reflection of the time base, described by von Wawrziniok,[63] is shown in Fig. 289. This circuit uses the vibration of an electrically-excited tuning fork which is maintained by a valve. Fig. 290 shows an oscillogram with a time scale obtained with this arrangement. The time scale was given by the vibration of a tuning fork of 230 cyc., the sinusoidal voltage oscillographed corresponding to a frequency of 10 000 cyc. In the arrangement of

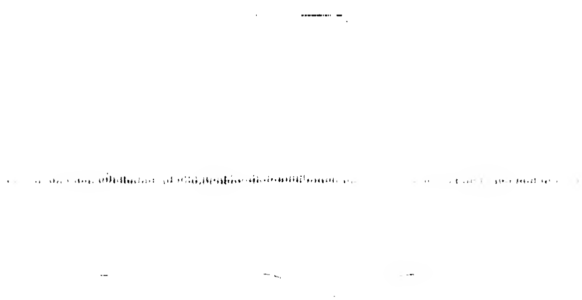


Fig. 290. Oscillogram of a Voltage of 10 000 cycles with a Time Scale (230 cycles) Produced by an Oscillating Mirror

Fig. 289 it is worthy of note that in addition to the time scale and oscillogram, it has been possible to record a further timing mark with the assistance of the electrometer device shown.

The use of a tuning fork constitutes a certain disadvantage in that it is limited to a single frequency. If, however, the oscillating mirror is connected to an electromagnetic or dynamic loudspeaker system instead of a tuning fork, this limitation disappears. Almost any frequency can then be chosen for the production of a time scale providing that generators of known low frequency are available. It is only above 2 000 cyc. that amplitudes are reduced to such an extent that satisfactory marking can no longer be obtained even when a large input of power is fed to the loudspeaker system. A further useful method of time-marking, which is of great importance in connexion with electrical time deflection, consists in superimposing on the bias voltage of the brightness control electrode short voltage impulses at known intervals of time. As a result, dark

or light points occur on the curve corresponding to the impulses. In order that the curve shall not be distorted by this method of time-marking, it is advisable, if possible, not to make the amplitude of the pulse unduly great and to keep it as brief as possible. The formation of short duration impulses of this kind can be done partly by mechanical means—rotating contacts and at higher frequencies by discharge oscillations. With the discharge device shown in Fig. 291, short impulses are very easily obtained, not by using the discharge voltage itself, but by the voltage drop which results from the discharge in the neon tube, this being of brief duration.

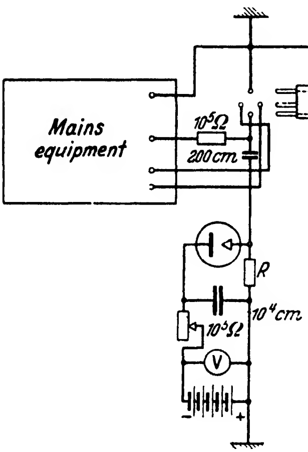


FIG. 291. CIRCUIT FOR PRODUCING A TIME SCALE ON THE OSCILLOGRAM BY INTENSITY CONTROL WITH THE AID OF VERY SHORT VOLTAGE IMPULSES

The resistance to be connected in series with the neon lamp must not exceed a few hundred ohms in order that the period of the discharge shall not be increased. Voltages sufficient to give distinctly recognizable light spots as indications are, however, produced by the discharge current of ordinary neon lamps.

VIII. COMPLETE EQUIPMENT

As all components used with oscillographs have been discussed in the earlier sections, this section can be confined to the consideration of purely constructional details of the complete apparatus. One of the main constructional points of cathode-ray tube apparatus is the method of supporting the tube. There are two ways of doing this. The tube may be fixed, and supported, and possibly mounted at eye level so that the fluorescent image can be observed from practically any direction. The possibility of observing the luminous screen from the front as well as from the inside is very important, particularly for general use in the laboratory, since switching controls are often such that they have to be made at some other point of the workshop and not close to the oscillograph. On the

right-hand side of Fig. 292 a form of support which has proved satisfactory in practice is shown The tube, in this case is adequately supported, but in spite of this there is space below the tube for arranging such parts of the measuring apparatus as may require connexion by short leads to the deflection plates. The holder is arranged so that it can be rotated through nearly 180°, so as to adjust the orientation of the co-ordinates as desired. The heating wires are arranged as far as possible to avoid coming near the neck of the tube, so that periodic deflection of the ray does not take place through the disturbing effect of stray fields from the heating wires when

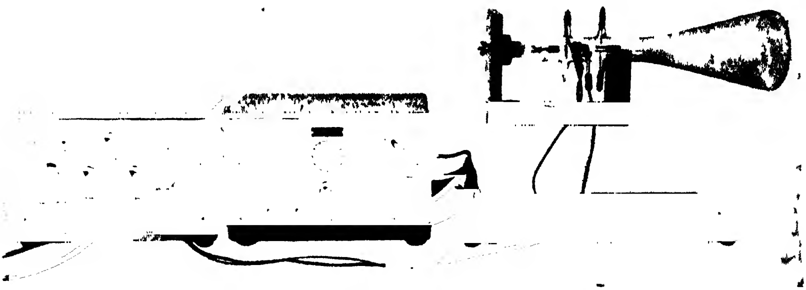


FIG. 292 OLD TYPE OF CATHODE-RAY TUBE EQUIPMENT CONNECTED TO MAINS AND TIME BASE CIRCUIT (*Leybold Nachf A G.*)

a.c. supply is employed. With modern types of tube construction, where large bulbs are used, and in particular with tubes having large diameter screens up to 30 cm. or more, it is desirable to build the tube into a protective housing or shield. This seems particularly desirable since, in the event of a burst with a large diameter tube, glass splinters are violently scattered about and may cause dangerous wounds. Indeed, safety devices are so far advanced in television equipment, that a special glass pane has been set up as an observation window in front of the fluorescent screen to ensure protection of the observer. In most of the complete equipments discussed further on, therefore, the tube is protected in this way.

In the photograph, Fig. 292, which is of an older form of apparatus, the mains unit and discharge equipment, each built into separate boxes, are next to the stand. This form of construction has become very popular, and this is due in a great measure to the fact that all currents and potentials with

the exception of the heater current of the "time" discharge circuits, are taken from a.c. mains. The design in which the

FIG. 293. MAINS EQUIPMENT AND ADJUSTABLE TUBE SUPPORT
(*General Radio*)

mains and time discharge units are separated may also be considered an advantage of the apparatus illustrated. Electrical time deflection is frequently not required. In such a case, the

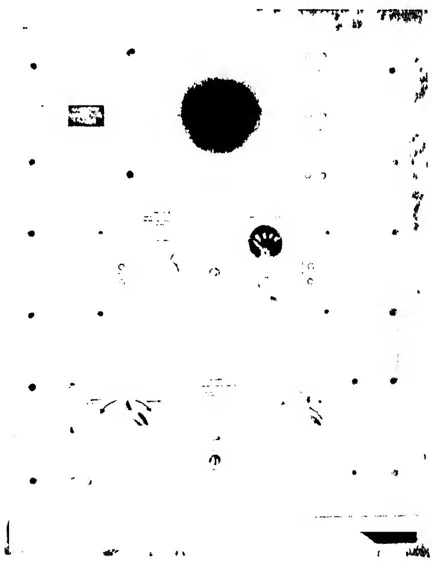


FIG. 294. SELF-CONTAINED APPARATUS WITH EASILY INTERCHANGEABLE PARTS

apparatus becomes simpler and more compact when the time base unit is removed. Sometimes the time-base unit or mains equipment is wanted for special laboratory purposes.

An installation developed by the General Radio Co. of Cambridge, America, is shown in Fig. 293. Here, again, the construction is one in which the tube and mains equipment are separated. The construction of the tube supports is worthy of note. The tube can be more or less inclined. Fig. 294 shows the construction of a complete apparatus in which are the essential parts assembled as a compact unit. Valves and amplifiers for increasing the sensitivity, as well as the mains equipment, are arranged one above the other, and the assembly

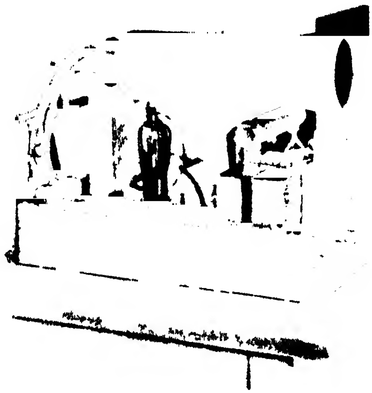


FIG. 295. EQUIPMENT FOR INVESTIGATING PERIODIC PHENOMENA INVOLVING MEASUREMENTS (*Leybold-v. Ardenne*)

is such that additional equipment can be added above the existing components according to the requirements.

The sizes of the parts are such that they can be inserted either in compartments or in the large common front panel. The mode of construction enables the maker to facilitate adaptation of the complete assembly to the demands to be made upon it. Another equipment is shown in Fig. 295. This illustration also gives further ideas for the arrangement of the tube and necessary equipment. All controls are on the front panel below the opening for the observation of the fluorescent screen. A permalloy tube surrounds the cathode-ray tube and screens it from stray magnetic fields.

Fig. 296 shows the circuit of a simple oscillograph with time deflection by means of a thyratron unit. An a.c. amplifier stage having a voltage divider connected in front of it increases the

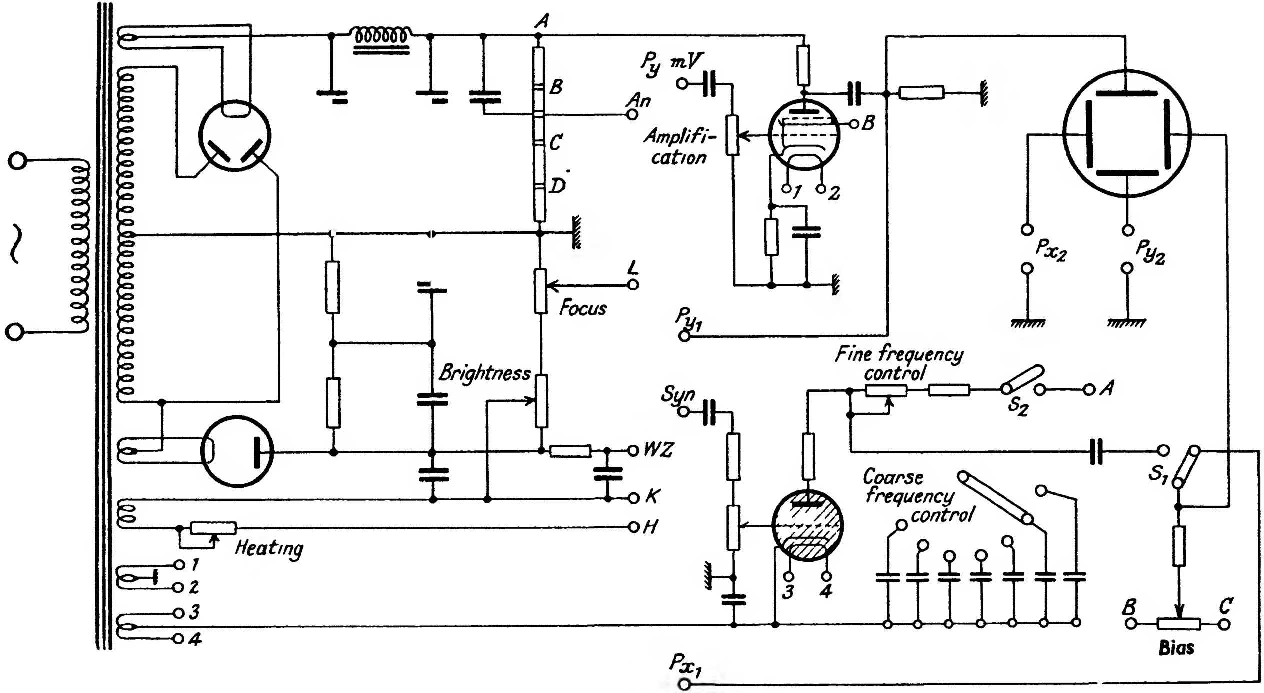


FIG. 296. A SIMPLE OSCILLOGRAPH WITH TIME DEFLECTION CONTROLLED BY A THYRATRON UNIT

measuring sensitivity of the oscillograph. If fluctuating phenomena including those of the d.c. components are to be oscillographed, the voltage under examination should be connected directly to the work deflection plates and the amplifier stage cut out. The switch S_1 mechanically coupled to S_2 serves to put in circuit the time deflection unit when required. The condenser of the saw-tooth oscillation circuit is charged by the full voltage of the mains equipment through an adjustable high ohmic resistance. The thyratron operates over a small portion of the charging curve which is sensibly linear. Attention is drawn to the mains equipment of the circuit discussed where the regulation of the voltage is carried out by means of an auxiliary half-wave rectifier valve. In the circuit of Fig. 296 the deflection voltages of the tube are unsymmetrical but in the large oscillograph arrangement of Fig. 297 the deflection voltages are symmetrical to the anode of the tube. The time base circuit which has been developed to secure high-frequency deflection oscillations by means of a saw-tooth valve discharge circuit, is symmetrical by reason of an auxiliary amplifying stage to the grid of which a part of the voltage of the saw-tooth generator is applied. This is obtained from a voltage divider whose performance is independent of frequency. The linear portion of the curve is obtained by means of a screen grid valve, the grid voltage of which is regulated by fine adjustment of frequency. The instant of discharge corresponds to the critical point on the valve characteristic. The discharge circuit produces deflection frequencies of the order of 10^6 cycles. By using capacity stages of higher values, frequencies down to 1 cycle per second can be produced. The decoupling units shown should be high enough to avoid feed back through the internal resistance of a common path to the mains portion of the equipment. The mains equipment used in the saw-tooth time base circuit as well as the symmetrical voltage measuring amplifier is common to both, and corresponds fundamentally to the mains section of the smaller oscillograph already discussed. Mention must also be made of the switching devices which connect the deflection plates to the amplifier, the time base unit, or direct to the voltage under examination according to the requirements of the problem.

Further to avoid disturbances from stray magnetic fields, arrangements should be made, especially with compactly designed equipments, that most of the mains transformers

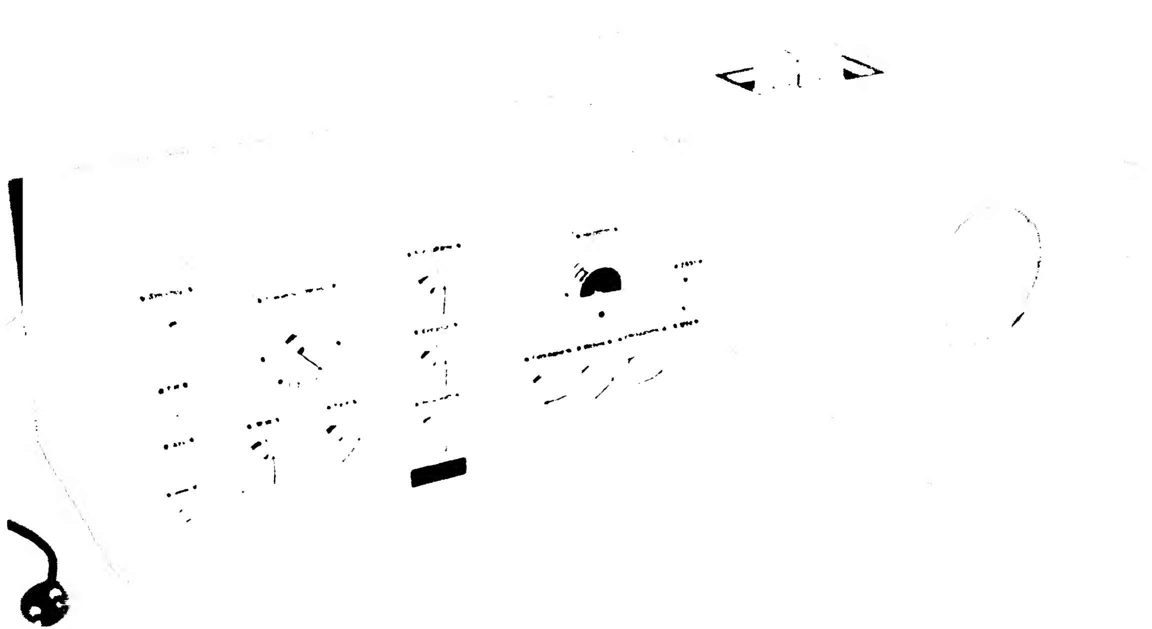


Fig. 298. Complete Equipment and Mains Units with High-vacuum Tube

employed have closed iron circuits and, furthermore, that they are so orientated that such stray fields as do remain cannot affect the path of the ray.

Another complete assembly for universal use in the laboratory is shown in Fig. 298. This consists of two boxes which are connected to each other by an eight-way high-tension cable. One box—the protecting housing—contains a high-vacuum tube with an 18-cm. diameter fluorescent screen. The box is some-

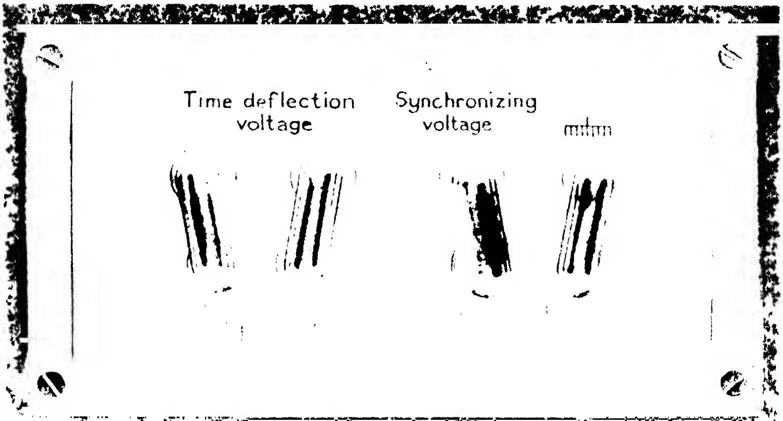


FIG. 299. VIEW OF THE SWITCHING ARRANGEMENT FOR CONNECTING THE DEFLECTION PLATES OF THE APPARATUS OF FIG. 298

what extended at the fluorescent screen end in order to exclude stray light from the screen. In the second box which is also screened, there is a mains equipment for anode voltages of 3 000 and a push-pull time base circuit which, at the anode voltage mentioned, supplies time discharge voltages which are sufficient for complete control over the whole surface of the large screen. The switchboard for the deflecting plate system (Fig. 299) which will be discussed briefly since its use is applicable to similar apparatus as well, is fixed above the box which excludes the light. It is very simple to adjust the apparatus to the particular problem of measurement in hand, by means of this switchboard. After removing the short-circuiting plug, the pairs of deflection plates, P_{x1}, P_{x2} and P_{y1}, P_{y2}, can be connected up as desired. The leads to the plates P_{x1} and P_{y1} are extremely short, so that the advantage of low earth and

distributed capacitances which exist in tubes with deflection plates led out at the side of tube, and the low capacitance construction of the switchboard, are retained. If time deflection is not required, plates P_{x1} and P_{x2} should be joined together and to an earthed terminal. If time deflection is required, connexions should be made in the way indicated on the left of the photograph of the switchboard.

The time deflection voltage symmetrical to earth is communicated to the first pair of plates facing the anode, so that sufficiently sharp focusing is secured at P_{y1} and P_{y2}, particularly during the investigation of small amplitudes even with unsymmetrical measuring voltages. For larger amplitudes a voltage symmetrical to earth should be applied to the plates P_{y1} and P_{y2} with the high-vacuum tube.

Lately, a very simple combination equipment called a "portable oscillograph" has attained considerable popularity. This form of construction, which has been produced by various makers (Cossor, Leybold, and von Ardenne) is distinguished by the fact that a 50-cyc. time deflection can be applied, the amplitude of which should be sufficiently increased to ensure that only the centre and consequently the linear portion of the sinusoidal deflecting voltage comes on the screen. In the Cossor construction, as well as in that developed by the author, blacking out of the fly-back traverse is effected by means of the brightness control electrode simultaneously with the switching on of the 50-cyc. time deflection. With such a very neat and handy piece of apparatus almost all the measurements discussed in this book with the exception of those which are only possible with the help of synchronized or unsynchronized discharge oscillations, can be carried out.

The forms of construction illustrated and discussed must be combined with appropriate auxiliary apparatus; for example, for observation with rotating mirrors or for photographic recording. As photographic recording is not generally the main function of the apparatus, it has not hitherto been customary in developing equipment to combine with it the necessary and sometimes very expensive accessories for this purpose. As a rule, the apparatus is constructed in such a way that by setting up the additional accessories on the same table, or by inter-connecting terminals, this auxiliary equipment is correctly orientated with respect to the optical system.

IX. Aids to Operation with the Cathode-ray Tube

There are many different auxiliaries for the operation of the cathode-ray tube, and these make investigations much simpler. These have been described partly in discussions on tubes and tube circuits so that only a brief reference is necessary here. A distinction should be drawn between internal devices

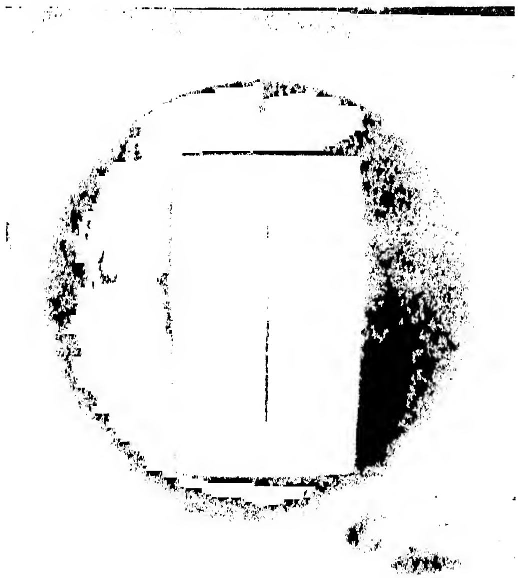


Fig. 300 Elimination of Secondary Illumination in the Path of the Fluorescent Spot Caused by Halos and Stray Electrons

which facilitate or improve the operation of the cathode ray tube and those external aids which are partly concerned with switching arrangements and partly with mechanical devices, and which not only bring about simplification but, to some extent also, increase the scope of the cathode-ray tube.

Framing the fluorescent stroke with a mask is an important aid in tracing and observing oscillograms with mechanical time deflection. Fig. 300 shows the way in which this is done. Secondary illumination caused by the development of halos and stray electrons (see Fig. 286) is excluded by this

masking. The clarity of the oscillogram is increased tremendously. The same method in a somewhat different form is used in Figs. 275 and 282. Care should be taken when mounting the tube that iron stands or supports are not used, as the residual permanent magnetism in them is often sufficient to give rise to a permanent deflection of the ray, away from the axis of the tube. If, in spite of the use of stands of non-magnetic material, displacement of the ray still occurs, this is frequently due to the fact that the electrodes are not exactly centred owing to mechanical vibration in transit. In this case, if the tube has an anode which can be magnetized, adjustment of the position of the ray can be effected by an additional magnetic field.

Displacement of the ray also frequently occurs by reason of the earth's field or stray fields from large masses of magnetic material in the neighbourhood where the investigations are being carried out; for instance, machine foundations. This disturbance can be very troublesome, particularly with low electron velocities. In this case, it is advisable to arrange the axis of the tube in the direction of the disturbing field so that its effect is neutralized. Often, it is quite sufficient, in order to compensate for the earth's field, to mount the tube vertically instead of horizontally, for since the earth's field is inclined at about 70°, the vertical component is much greater than the horizontal component. For small displacements of the ray permanent magnets suffice to obtain adjustment free from distortion; but for strong disturbing fields compensating coils covering the entire length of the oscillograph are used. In connexion with external accessories, reference should be made to the chapter on mains equipment (Chapter II, Section I), where mention is made of protective resistances. An extension of the range of utility of the cathode-ray tube can be attained by using the process for multi-characteristic tracing, already referred to briefly in the chapter on tracing characteristics with electrical time deflection.

There are, in principle, two ways of doing this. Tracing each curve in turn and tracing points on each curve alternately, so that persistence of vision makes all the points blend together and appear as one outline. [68]

The first process, which has been further developed by Hollmann [69] in the characteristic comparator, employs in one type a rotary commutator or switch which connects

mechanically the anode voltage of each valve to be compared in turn to the deflecting plates by means of a special cam-

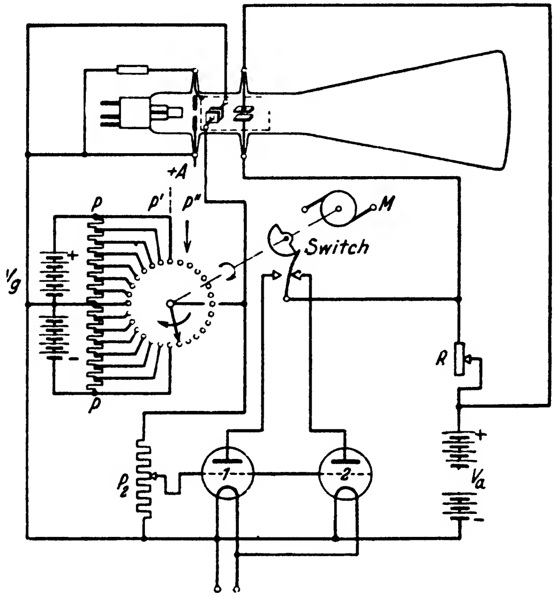


FIG. 301. CHARACTERISTIC COMPARATOR WITH ROTARY SWITCH

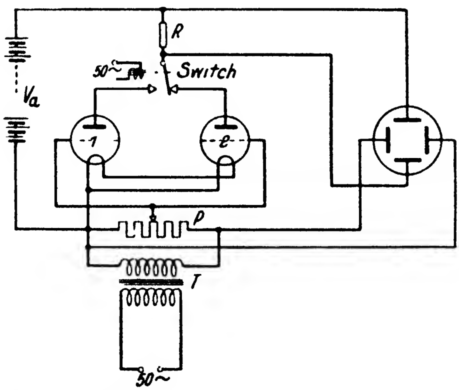


FIG. 302. CHARACTERISTIC COMPARATOR WITH VIBRATING SWITCH

shaped contact, so that the outline of the characteristic of each valve follows one another.

At the same time the appropriate grid voltage is switched on

and varied by means of a potentiometer arm rotating on the same axis. In place of the commutator or rotary switch an electromagnetic buzzer (pendulum convertor) can also be used (Fig. 302), which when operated from a.c. lighting supply voltage and with correctly adjusted contacts, enables the entire

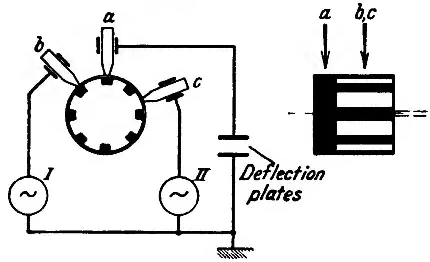


FIG. 303. DIAGRAM OF A COMMUTATOR SWITCH FOR MAKING TWO CURVES VISIBLE

outline of the characteristic to be obtained. The abscissa tracing takes place automatically if a short interruption exists between both switch contacts. In the process of curve tracing by separate points a rotary commutator switch (Figs. 303 and

FIG. 304. VIEW OF COMMUTATOR SWITCH SUITABLE FOR MAKING 100 CHANGE-OVERS PER SEC

304) is employed. By arranging the spacing of the three brushes each of the two a.c. voltages to be compared can be applied in turn to the "work" deflection plates. The interruptions in the curve which necessarily occur become smaller for a given frequency to be examined the higher the rate of rotation or speed

of the commutator. The number of revolutions of the switch should therefore be as high and the number of bars as great as mechanical conditions of operation will permit[70] This is particularly applicable to the tracing of single non-recurrent processes, but the interruptions in the outline of the curve

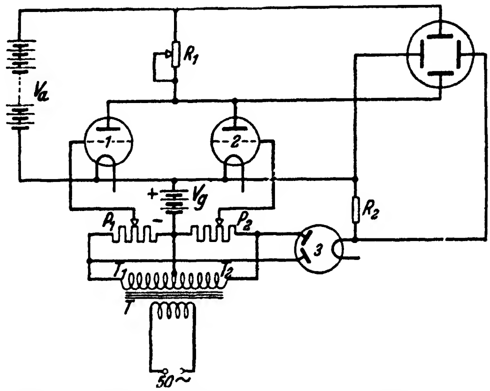


FIG. 305. CHARACTERISTIC COMPARATOR WITH CHANGE-OVER ACTUATED BY A VALVE CIRCUIT

cannot be less than the points of the curve which are actually traced. In tracing high-frequency phenomena, switching

FIG. 306. CO-ORDINATE SCALE ON THE FLUORESCENT SCREEN

operations in both cases should be carried out by valves. An arrangement for alternate tracing of each curve with switching arrangements controlled by a valve is shown in Fig. 305.[64]

It is often very desirable to evaluate the oscillogram directly on the luminous screen. In order to facilitate the fixing of a scale, rectangular co-ordinates on the outside of the screen

(Fig. 306) are recommended. If it is desired to read amplitude values only, the auxiliary apparatus of Fig. 307 enables exact measurement to be made. It consists of two measuring arms

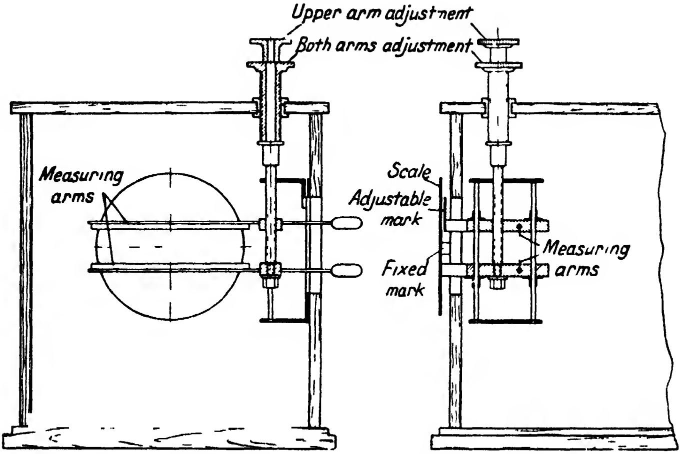


FIG. 307. AUXILIARY APPARATUS FOR MEASURING VALUES OF AMPLITUDE.

adjustable in the vertical direction, the distance apart of which can be read off on a scale. This scale can also be cali-

FIG. 308. SCALE FOR DIRECT READING OF VOLTAGE

brated in terms of voltage. If only one deflection is applied to the tube, it is sufficient to arrange a measuring scale in front of the luminous screen as in Fig. 308.

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CHAPTER III

THE CATHODE-RAY TUBE AND AUXILIARY EQUIPMENT FOR MAKING MEASUREMENTS

Previous chapters of this book have dealt with the cathode-ray tube, its principles and construction, as well as the accessory equipment required for operation with it. The accessories have been described in detail in so far as their use is essential to the working of the tube. The principal section to which we now come covers the most important special uses of the cathode-ray tube as a measuring instrument. These uses will only be described so far as they involve new combinations of the tube and its accessories, and therefore several of them are not described in detail as they are in the chapter on the tube and its accessory apparatus. First, a survey will be given of the possible uses of the cathode-ray tube.

I. The Observation of the Path of the Ray as an Independent Problem

The original purpose of the high-vacuum, as well as the gas-filled, tube was the tracing of the relation between time and an independent variable. Gas-filled tubes possess an illuminating ray which is limited in space. By using a modern system for ray production with a relatively high gas pressure and a gas which is particularly good from an illumination point of view, e.g. helium, very intense and narrow illuminating beams can be produced. Such tubes, therefore, facilitate not only the tracing of oscillograms by the movement of the fluorescent spot, but also, by direct observation of the tube itself, investigations of the conditions under which rays are produced and stray fields which affect them. For these purposes, the low-voltage cathode-ray tube is particularly suitable. The addition of special deflecting electrodes for measurements of this kind is not essential. As already mentioned in earlier chapters, ionization phenomena and conditions of focusing can be investigated by variation of the gas pressure, the type of gas, its temperature, the number of electrons and their velocity. The

diffusion of electrons in a dense gas can also be calculated from the spreading out of the rays which results. The return conduction of the current in the cathode-ray tube, of both ions and electrons, can be recognized by the luminous excitation of the corresponding current path. The quantitative investigation of these return currents is made possible by measuring the current passing to each individual electrode.

Ionization can be recognized from the resultant enlargement of the spot, under high-frequency deflection of the ray. The distribution of potential in the ray path can be determined by means of the Aston crossed cathode-ray method in which

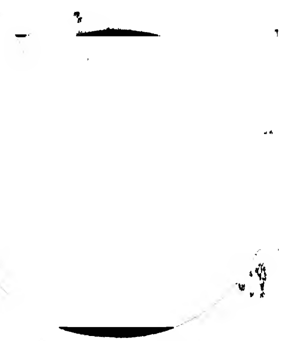


FIG. 309. CATHODE RAY DEFLECTED IN A MAGNETIC FIELD

the deflection of a second cathode-ray crossing the primary is measured. Attention must, however, be given to the possibility of potential changes in the path of the primary ray occurring owing to the second cathode-ray crossing it. Under the influence of magnetic fields the electron jet is deflected from its linear path (see above) to one which is part of a circle (Fig. 309).

The strength of the field influencing the cathode ray can be calculated from the radius of curvature of the deflected path, or if the length of the ray path is known, from the deflection of the fluorescent spot from the origin position on the screen.[1] In this way any magnetic field can be explored point by point with the cathode-ray tube. Instead of calculating the field strength from each individual deflection, it is possible to calibrate the tube initially from a known and uniform field. In this case a scale in the form of a concentric circle can be brought

up directly to the luminous screen. It is important when doing this to ensure that the tube is in a space free from any stray fields, and that the effect of the earth's field is compensated. As a space free from magnetic field, either the inside of two interlocking soft iron tubes can be used or the earth's field may be compensated by as large a current coil as possible. This current coil can also be used for calibrating the tube. Fig. 310 shows an equipment for measuring the earth's field, which was developed by the A.E.G. In this instance the tube is mounted in a manner similar to the telescope of a theodolite, and is easily turned about the vertical or horizontal axis. Arcs of circles facilitate the reading of the magnitude of the angles. A special arrangement enables the tube to be turned exactly through 90° which is essential for determining the magnitude of the field. The measuring equipment has the advantage of recording the two important characteristics of the field (magnitude and direction) within a fraction of a minute. When the tube is vertical, the horizontal component of the earth's field which is at right angles to the path of the ray can be determined alone. At the same time the electron jet is deflected at right angles to the magnetic lines of force and the fluorescent spot is deflected eastwards. The use of this method of ascertaining the horizontal component of the field as a direction indicator led to the electron ray aeronautical compass developed by Brüche (Fig. 311).

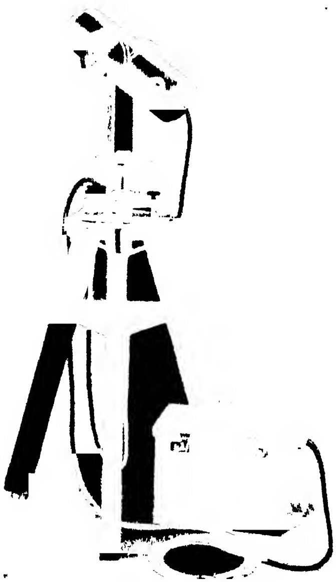


FIG. 310. ELECTRON RAY MEASURING EQUIPMENT FOR RAPID ESTIMATION OF THE MAGNITUDE AND DIRECTION OF AN EXTENDED MAGNETIC FIELD

Up to now, the direction and magnitude of the earth's field, which change from place to place, have been ascertained with reference to the surface of the earth. With the aeroplane compass the direction of north, or in the aeroplane the direction

of flight, is determined by measurements in the magnetic field of the earth which is known, and the orientation with reference to the earth's field can be ascertained. The impossibility of excluding the effect of the vertical component of the earth's field when the aeroplane is inclined, as well as the inertia of the needle, must be considered as a disadvantage of the magnetic compass. Apart from the freedom from inertia of the electron jet, the latter registers the horizontal and vertical components individually and brings them separately to the indicator; in this way it not only avoids errors of the magnetic

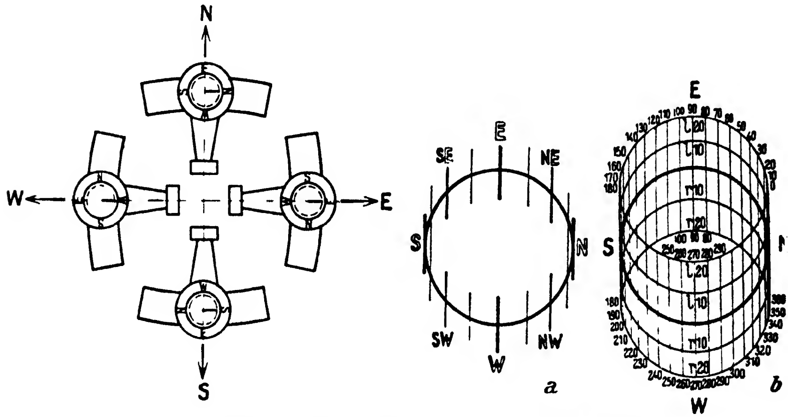


FIG. 311. ELECTRON-RAY COMPASS FOR AIRCRAFT (*Bruche*)

compass, but also enables positive indication of the inclination of the aeroplane to be made. If the tube and aeroplane are turned about a vertical axis, the electron jet maintains its position unaltered relative to the magnetic field of the earth, and the fluorescent spot is always deflected eastwards. If, as in Fig. 311, directions in the form of a compass card are traced on the screen, this provides for orientation. When the aeroplane turns the spot moves; it traces the so-called direction circle. If the tube is not kept vertical but inclined in space, the direction circle is brought under the influence of the vertical component of the earth's field. The electron compass can also be used as an inclinometer in the same way (Fig. 311).

Fig. 311 shows on the right a direction diagram for different vertical inclinations of the aeroplane. A disadvantage of the

electron ray compass is that the method of indication is not immediately obvious to the pilot. He must always work out mentally the actual flying position from the indication of the equipment. A cathode-ray tube with all the necessary equipment for an electron ray compass is shown in Fig. 312. The observation tube for the luminous screen can be seen in the upper portion of the equipment. As the electron ray is deflected in two dimensions by the action of extended magnetic fields, it is possible to make experiments on models of such fields with the

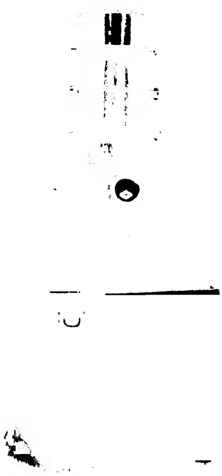


FIG. 312. VIEW OF ELECTRON-RAY AIRCRAFT COMPASS

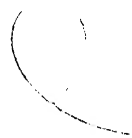


FIG. 313. SPATIAL DEFLECTION OF THE CATHODE RAY INTO A LOOP

FIG. 314. SPATIAL DEFLECTION OF THE CATHODE RAY BY THE MAGNETIC FIELD OF COILS

cathode-ray tube. Examples of spatial deflection of the cathode ray are shown in Figs. 313 and 314. Experiments on models to confirm the Stormer theory of the polar aurorae have been made by Brüche.(2) According to the Stormer theory, the polar aurorae are caused by streams of electrons which reach the earth from sun spots. After arduous observations on the northern lights and also by calculation, Stormer showed that these rays through the influence of the earth's magnetic field, can reach the earth in narrowly restricted beams either causing well-known luminous phenomena in the atmosphere, or returning back into space. In order to test the theory, Bruche subjected gas-focused rays to the influence of magnetic fields which corresponded approximately to the shape of the earth's field. These experiments are of particular importance in research into the physical state of the Heaviside layer. The reflection and refraction of high-frequency waves can also be imitated by means of experiments on models. The high-frequency waves, according to the de Broglie theory, are substituted by electron rays of corresponding velocity, and these are deflected at one or more wire grids which are at different potentials. The tube in Fig. 315 has been developed for instruction and practical work in physics. The system for producing the rays is so arranged that the electron stream can develop into a circular path in a uniform field. According to A. Bestelmeyer the value e/m is determined from the diameter of the circular path, the electron velocity, and the strength of the magnetic field.(3)

FIG. 315. VIEW OF A TUBE FOR DETERMINING THE VALUE OF e/m FROM THE RAY PATH

II. Use of the Cathode-ray Tube in High-frequency Technique

The chief function of the cathode-ray tube and the one for which it was originally developed by its inventor, Ferdinand Braun, is still the recording of phenomena which vary with time. Since, as a result of its freedom from inertia, it is possible for the tube to trace high velocity phenomena, and it represents the most suitable instrument for making high-frequency measurements. The classical work of Zenneck and his pupils in particular has shown that high-frequency investigations of very varied character can be carried out with the cathode-ray tube. The characteristics of the circuit components used in high-frequency work, as well as the characteristic of the equipment as a whole, can be recorded faithfully. Tracing operations which are of short duration, as well as the control of high-frequency equipment over long periods, can be carried out in an ideal manner with the cathode-ray tube. The superiority of the high-vacuum tube over the gas-filled type is particularly clear in its use for high-frequency work. Most important of all, it eliminates anomalies of frequency which are caused by gas filling, and are most troublesome in this type of work. Furthermore, the ohmic resistance between the plates which in the gas-filled tube is of the order of 1 MΩ., is high enough to be left out of account.

1. **Examination of Individual Components.** The fundamental element of all high-frequency arrangements is the oscillatory circuit formed by the electromagnetic and electrostatic sources of energy, the inductance and the capacitance. Investigation of the capacitance and inductance used in the oscillatory circuit is also essential, if it is required to know the way in which this circuit functions.

(A) Examination of Condensers. The investigation of capacitances is involved in various problems. Electrically the determination of the value of the capacitance may be looked upon as the most important measurement. It is determined either by finding its absolute value, or by comparative measurements. An extension of this measurement is the determination of the ohmic conductance. Methods of measurement which permit of the determination of both these values will be advantageous particularly for tests during mass production. A further characteristic of the condenser is its puncturing voltage or field

strength to cause breakdown. The time of commencement of the breakdown, and the total time and magnitude of the voltage, can be recorded by the low-voltage tube, though registration of the variation of voltage and current during the breakdown period is scarcely possible. This problem, which is important in making clear the theory of the mechanism of the breakdown, remains primarily subject to treatment by high or medium voltage oscillographs. Allied to the question of breakdown is the oscillographic determination and comparison of operating voltages under test conditions.

Measurement of capacitance can be carried out very simply with the cathode-ray tube, using it as a voltmeter or ammeter. A typical arrangement for the measurement of complex resistances is shown in Fig. 316. Here the voltage which is available by direct connexion to a source of very small internal resistance is measured, and also that across a known resistance R_p, which is in series with the resistance to be measured. The range of measurement can be altered within wide limits by the values of the generator voltage and R_p. The only limitation in the selection of the value R_p is merely that it must be small compared with the internal plate resistance of the tube. In tubes with low gas pressure and return current guard-ring electrodes, or in high-vacuum tubes, the resistance may be 100 000 ohms if the frequency measured and the capacitance of the deflecting plate system is so small that the shunting effect of R_p due to its capacitance can be ignored. The accuracy of measurement possible depends on the characteristics of the tube, and particularly on the diameter of the focused spot and the constancy of the generator voltage during the time required for carrying out both measurements. This simple arrangement is only suitable for very accurate capacitance measurements when used in conjunction with modern tubes. It is very suitable for bulk testing of capacitances when rapid measurement is of importance. One disadvantage of the arrangement is that the voltage division depends on the complex resistance, and not on the reactance of the condenser. It is essential, therefore, when testing condensers by this method, to sort out

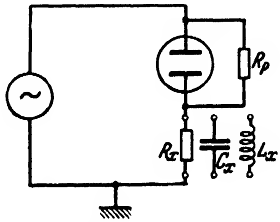


FIG. 316. ARRANGEMENT FOR MEASURING COMPLEX RESISTANCES

beforehand those whose ohmic conductance is extraordinarily high.

Bridge methods are usually employed where the most accurate determinations of capacitance are involved. With a preliminary amplifier, the cathode-ray tube is very suitable as a detector for such circuits. Adjustment of the zero balance can be made much more exactly by optical means which are free from the possible disturbance of factory noise. If the source supplying the bridge does not give a sine wave voltage, the determination of the null point with the cathode-ray tube is much more accurate than by the usual acoustic method, and not only the amplitude but the shape of the curve with time deflection can be observed. As an indicator for bridge circuits, the cathode-ray tube has considerable advantages over galvanometers, valve voltmeters, and other apparatus by reason of its freedom from inertia.

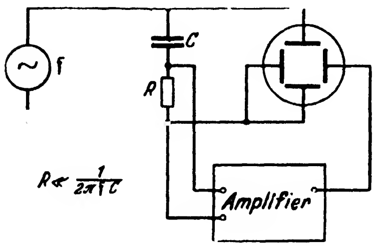


FIG. 317. CIRCUIT FOR MEASURING DIELECTRIC LOSSES

Direct methods of measurement and bridge circuits are also used for determining the magnitude of other characteristics, such as the ohmic conductance. As a rule, direct measurement involves the use of the second pair of plates of the tube in order to determine phase changes. A circuit frequently used is shown in Fig. 317. Here the sinusoidal voltage of the generator, having a frequency f, is measured by the vertical pair of plates, and the reactance current flowing through the condenser by the horizontal pair of plates. The current is measured as a drop in voltage across the resistance R by the aid of an amplifier. The amplifier is necessary in examination of small currents, so that the resistance R may be kept small compared with the resistance of C, and in this way disturbance by phase changes is avoided. Also, the amplifier must not give rise to phase-shift. Fundamentally, resistance coupled amplifiers are necessary here, since they alone are free from this complication. The amplifier should be designed so that its maximum amplification occurs at the frequency of the generator (see Chapter III, pages 380–387). Here, again, the condition that the internal resistance of the generator shall be small compared with the internal

plate resistance of the tube, must be fulfilled if possible by the use of a high-vacuum tube. As the voltage components from the generator are 90° out of phase a circular diagram appears on the luminous screen provided that the degree of amplification is suitably adjusted, and that the condenser has perfect insulation. If, however, such conductance exists, the circular figure would be modulated by the addition of the current involved, which would be in phase with the generator voltage. Resistance components come into prominence particularly if the conductance depends on amplitude, as in the case of neon or flash-over discharges. If the condenser losses are small it would appear to be best for the voltage of the ordinate pair of plates to be formed by the reactance of an auxiliary condenser with the assistance of a resistance and amplifier. In this way the circular diagram becomes a straight line, and the small phase angles begin to be noticeable by the formation of loops. This is, of course, subject to the condition that the comparison condenser is free from losses. The frequency range of the measuring equipment when amplifiers are used is not limited by the upper frequency limit of the aperiodic amplifier, but by the frequency of maximum amplification advocated above. By using small coupling condensers this frequency can be displaced towards the higher range. As the range of frequencies covered by the amplifier decreases, however, it becomes increasingly necessary that the frequency of the generator should coincide exactly with the frequency of maximum amplification of the amplifier in order that the correct phase relations may be obtained. With regard to measurement of arcing voltage and the outline of the operating and test voltages, it should be noted that the measuring range of low voltage tubes usually necessitates the use of voltage dividers discussed in detail previously, if a specially low sensitivity tube is not available (e.g. the tube in Fig. 142). Finally, for the sake of completeness, it must be mentioned that the dielectric constants, as well as the capacitance, can, of course, be investigated by similar circuits. For example, by coupling an electrical time deflection to a frequency regulator of the generator any variation of frequency due to the dielectric constants can be made visible on the screen. The necessary circuit arrangement and details about the measurement of very small changes in capacitance have already been given. (Chapter II, pp. 227–8.)

(B) Examination of Chokes and Transformers. For the investigation of the electromagnetic sources of energy in oscillatory circuit chokes or transformers, methods similar to those described in the previous section for the examination of capacitances should be used. The methods used for measuring the electromagnetic sources are naturally modifications of those used for the measurement of the electrostatic sources. The dielectric constants are replaced by the permeability constants. With inductances, distinction must be made between magnetic and non-magnetic material in the path of the magnetic flux. For non-magnetic material the permeability is constant $= 1$, and for magnetic substances it is a variable whose value in theory can scarcely be specified. The determination of the value of resistance can be omitted here. For measurement of the inductance with the cathode ray there are again direct and indirect methods as in the case of measuring capacitance. In the direct method (Fig. 316, arrangement for measuring complex resistances) the condenser is simply substituted by the inductance. Naturally, the same principles concerning the resistances and voltages employed in this circuit apply as in the case of measuring capacitance. The bridge method is also suitable for precise measurement of inductance, but the self-capacitance of the inductance must be taken into account if errors in measurement are to be avoided. To reduce errors due to this cause to a minimum, the frequency of the generator should be kept as low as possible. In the same way the capacitance of a choke or transformer in the arrangement shown can be determined.

With iron-cored chokes and transformers, a knowledge of the permeability becomes important on account of distortion caused by its variable magnitude. The cathode-ray tube is particularly suitable for making such measurements, since it can furnish the whole curve from which such particulars can be obtained. The magnetic permeability is defined as $\mu = B/H$, where B is the induction and H the strength of the magnetic field. This definition leads to difficulties with reference to any magnetic cycle since two values of B are obtained for each value of H, one on the rising and one on the falling branch of the hysteresis curve. Both these values of the permeability correspond to the field strength only in the cycle selected which is indicated by a definite maximum induction. If the process extends to a different value of maximum

induction, then there are two other values of permeability corresponding to the same value of H. Consequently, there is an unlimited number of values assignable to μ. If it is decided to take the value of permeability from the magnetization curve, which is traversed until saturation occurs, then an unlimited number of values corresponding to H is no longer obtained but only two for each value of H, one on the upward and one on the downward branch of the curve. This difficulty is avoided for d.c. by stipulating that the value of the permeability is taken from the first hysteresis curve. The conditions become much more difficult in the case of magnetization by alternating fields. These experiments show very clearly the superiority of the cathode-ray tube for tracing magnetic hysteresis curves. In consequence of its freedom from inertia the cathode-ray tube, especially the high-vacuum type, permits of the use of higher frequencies for investigations. Apart from determining the permeability, the tracing of the dynamic magnetization curve is important technically in calculating the iron losses which are given by the area enclosed by the hysteresis curve.

According to the Angström[(4)] process, the cathode ray is deflected in one direction by the magnetic field of a pair of coils with an open iron core, and in a direction at right angles to it by the field of an air-cored coil, both pairs of coils being in series. The air-core coils give rise to a deflection proportional to the magnetizing current of the pair of iron-cored coils, and the deflection of the latter is proportional to the flux in the iron core, but this flux is determined only partly by the magnetic properties of the iron under investigation, and is not by any means proportional to the induction B in the iron. In fact, the flux ϕ is only partly dependent on the iron as long as the magnetic path in the iron and the air are of equal magnitude. Madelung's[(5)] arrangement endeavours to get over these disadvantages. In the latter process, the magnetizing coils are wound on two glass tubes bent to the form of a semicircle which contain the material under examination in the shape of a slotted ring, and the slit encircles the cathode-ray tube at its narrowest part. This has the advantage of providing a much more uniform field at the deflecting point than if only one pole is used compared with the Angström method, distortion of the curve is thus avoided. Furthermore, the material is examined as a closed ring as a result of which the deflection of the cathode ray for the same length of iron and magnetization is increased.

But even in the Madelung arrangement for tracing the *I-H* curve there is also a source of error due to the air gap in the iron ring necessitated by the cathode-ray tube. As a result of the air gap, spreading of the field, which is dependent on the permeability, occurs, and since the value of the permeability is not known, the extent of this cannot be calculated.

A correct value of the magnetization curve can only be obtained when a closed iron core is employed. Fassbender and Hupka[6] take the curve of $d\phi/dt$ against t from which they obtain, by graphic integration, the relation between ϕ and t. Furthermore, they photograph the curve showing the relation between i and t, or accept it as being sinusoidal, and obtain by construction the relation between ϕ and i, as the required hysteresis curve. This indirect procedure wastes a good deal of time, and is not very accurate. These disadvantages are avoided by Kruger and Plendl in their method with a closed iron core for direct photography of the magnetization curve which has already been shown in Chapter II, pp. 289–294, and Fig. 257. By this process, the way in which the magnetizing curve depends on various factors, e.g. saturation, thickness of plate, the size of the air gap and the existing residual magnetism, can be seen. The effect of frequency and temperature can also be made clear in the same way by the use of the cathode-ray tube. Apart from obtaining the magnetizing curve itself it is of interest to ascertain the influence of the shape of the curve on various circuits in which iron-cored inductances are used. For this purpose, on account of its freedom from inertia, the cathode-ray tube is a very suitable instrument for measurement, particularly at high frequencies. As previously indicated, distortion of the primary voltage impressed on a magnetic circuit occurs as a result of the work done in magnetizing the iron and the variation of the permeability.

The extent of the distortion varies according to whether the rising portion of the characteristic is concerned or whether the region of saturation is involved. These distortions are usefully employed in practice by a process in which the frequencies are doubled by iron transformers.[7] Such distortions can be recorded in a simple way with the cathode-ray tube. The method of frequency multiplication consists in saturating an iron-cored choke, which is in series with an inductance on a.c. supply, to such an extent that the magnetic reversal

occurs in a fraction of a half-cycle of the current in the circuit, i.e. in the so-called *impulse time*, as a result of which the voltage at the terminals of the choke is of a very "peaky" shape. An oscillatory circuit controlled by this peak is excited into self-oscillation, the frequency being determined by the inductance and capacitance, in the oscillatory circuit. The iron core represents the generator of the harmonic frequencies which occur. The effects of the additional circuit connexions in this arrangement can be oscillographed by means of the cathode-ray tube. For this purpose, two coils without iron cores, of low

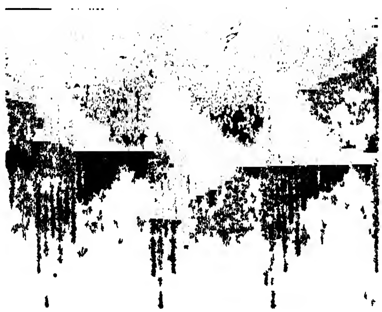


FIG. 318. UNSYMMETRICAL CHARACTER OF AN OSCILLOGRAM OF THE VOWEL "E" DUE TO IRON

inductance and resistance, are connected in the forced oscillation circuit, and these serve for magnetic deflection of the cathode-ray tube in tracing the outline of the current in the secondary circuit.

The relative amplitudes of the secondary voltage which is produced are shown according to whether the rising or falling branch of the magnetizing curve is traversed. The difference in amplitude can be recognized from Fig. 318, which shows an oscillogram of the vowel "e." Similar differences are shown by the oscillogram of the frequency characteristic of a transformer connected to a valve (Fig. 319), which was taken by the slow photographic process for recording amplitudes discussed in Chapter II, pp. 328–332. The differences in amplitude resulting from distortion due to the iron at low frequencies can be clearly seen. The curve traced shows the resulting frequency characteristic resulting from the joint operation of the transformer and the valve. In the case of the transformer

stage investigated, the internal resistance of the valve causes a damping which is sufficiently great to transfer frequencies of the audible range fairly uniformly. The record shown is particularly interesting because the resonance in this case at about 7 000 cyc. is strongly marked.

The tracing of the process by which transients are built up is a problem which recurs frequently in connexion with choke resistance circuits. The object of the investigations is usually to trace the relative time constants. As a rule, measurement is directed towards oscillographing the outline of the current and voltage as a result of a surge due to switching on. The charging

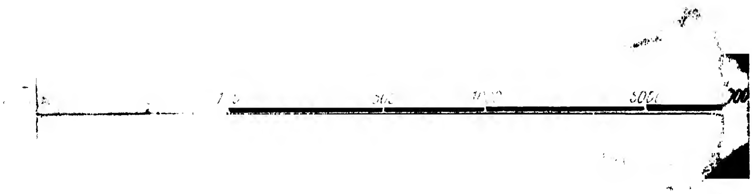


FIG. 319. RECORDED FREQUENCY OF A TRANSFORMER STAGE WITH STRONGLY PRONOUNCED STRAY RESONANCE AND CONSIDERABLE DISTORTION DUE TO FREQUENCIES BELOW 100 CYCLES.

and discharging can also be studied by means of condenser resistance arrangements. Curves of such units with different time constants obtained in practice are given later (Figs. 338, 339). If both sources of energy are present at the same time in the circuit under examination, the oscillogram will not only show the formation and fading, but also the periodic alternation of energy between the two sources.

(c) INVESTIGATION OF OSCILLATORY CIRCUITS. If an impulse is given to an oscillatory circuit containing inductance and capacitance, in the manner indicated, a damped oscillation is produced. If this damped oscillation is recorded with the cathode-ray tube, the resulting oscillogram shows the gradual change of the amplitudes caused by losses in the oscillatory circuit. This is, of course, conditional on the time deflection being of the same order as the increasing or fading transient oscillations. Fig. 320 shows a typical oscillogram of a damped oscillation. The logarithmic decrement of the process can be

read direct from the envelope of the amplitude curve. Where high-frequency oscillatory circuits are involved, the impulse should be repeated periodically and the time deflection synchronized with it when the tracing is carried out with the low-

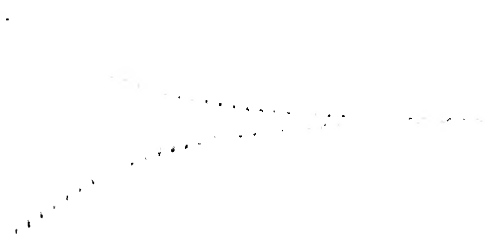


FIG 320. OSCILLOGRAM OF A DAMPED OSCILLATION

voltage cathode-ray tube. Wherever definite oscillatory circuits are involved, and where the characteristics are independent of the amplitudes, the tracing of the complete outline of the oscillation is chiefly of importance for demonstration purposes. It is different in the case where L, or perhaps C or R as well depend on amplitude. In such a case, the cathode-ray tube will furnish a means of forming an estimate of the effect of such factors on the outline of oscillation in a very simple manner.

FIG. 321. VOLTAGE OUTLINE IN COUPLED CIRCUITS

The registration of the outline of the current and voltage curves in coupled oscillatory circuits is also of primary importance for teaching purposes. Fig. 321 shows a typical voltage outline of a coupled circuit. A further oscillogram (measured by Kammerloher) which shows highly-damped oscillations very clearly in tightly-coupled circuits is shown in Fig. 322. Determination of the increasing or fading transient oscillation is of particular importance when testing transmitters and receivers for suitability for high-speed telegraphy. In this case the

time constants are measured and these must be kept small compared with the duration of the code signals. With very lightly-damped arrangements the times involved in building up or fading of the transient oscillations, as shown above, are

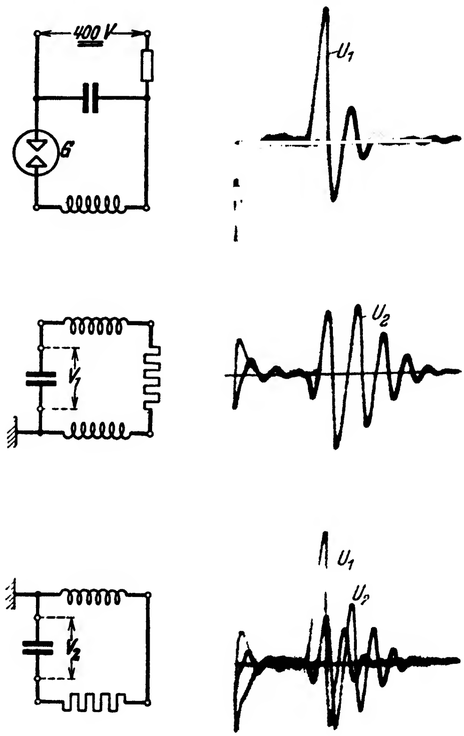


FIG. 322. DAMPED OSCILLATION IN TIGHTLY-COUPLED CIRCUITS

of the same order of duration as the low frequencies. With lightly-damped arrangements it is advantageous to take the damping decrement from the fading curve. In all other cases, the method described below should be used. For single high-frequency oscillatory circuits, with coupled h.f. circuits and complete h.f. amplifiers, the resulting frequency characteristic can be made directly visible by the method described in Chapter II, page 289 *et seq.* This method, which consists

in allowing the frequency of a transmitter to swing in synchronism with an electrical time deflection, can be altered somewhat for h.f. investigations. For example, the fluctuation in frequency can be produced by a condenser circuit electrically excited, one plate of which is formed by a telephone membrane. If this fluctuating capacitance is applied to the oscillatory circuit of a simple superheterodyne circuit, high and low frequencies are produced as intermediates according to design.[8] The resulting frequency characteristic shows, in the case of an oscillatory circuit, the resonance curve as the

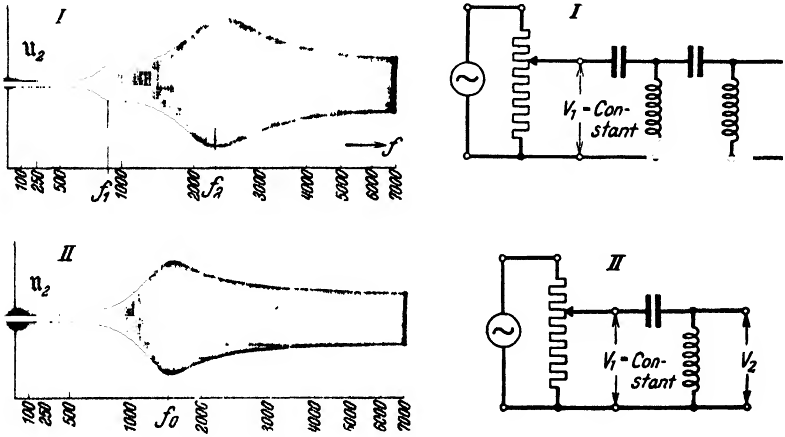


FIG. 323. FREQUENCY CHARACTERISTIC OF A CONDENSER NETWORK

envelope of an illuminated surface. From it, the tuning band and therefore the damping decrement can be determined directly. From the resonance curve and at least one of the other constants of the oscillatory circuit, the values of its characteristics (resistance at resonance, resistance of the coil) can be calculated according to known equations. The fact that the frequency characteristic of coupled units can be made visible is of particular importance in practice, especially in the case of h.f. amplifiers where several circuits are ganged. The freedom from inertia in tracing the characteristic makes careful synchronization of the oscillatory circuit and its control possible.

The process described is frequently used for adjusting single knob control receivers for operation tests. If the selectivity

of the units under investigation is very high, or if the natural frequency lies in the low-frequency range, it is not possible to trace the frequency characteristic on the screen of the tube without flicker. Indeed, it is necessary to reduce the frequency change per unit time. Fig. 323 shows the response curve of a condenser network obtained with slow frequency traverse (measurement by Kammerloher).

(D) EXAMINATION OF VALVES. The most important features of thermionic valves—slope, amplification factor, internal impedance, saturation current, and finally the position and extent of linearity—are obtained from their characteristic curves. The fundamental advantages of tracing characteristics by means of the cathode-ray tube, as well as the circuits used in the solution of the problem, have been discussed in detail (Chapter II, page 289 *et seq*). It will be sufficient, therefore, to mention merely additional points which occur in the practical examination of valves.[9]

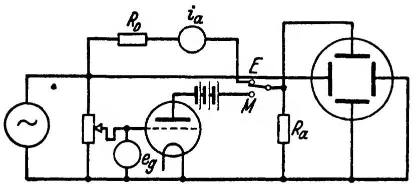


FIG. 324. CIRCUIT EMBODYING THE ESSENTIALS REQUIRED FOR TRACING CHARACTERISTICS

The appearance of the characteristic and the addition of co-ordinate scales across it do not alone enable an opinion to be formed about the properties of the valve. In fact, it is still necessary to calibrate both scales. Fig. 324 shows a simple circuit arrangement which enables the ordinate and abscissae scales to be obtained quickly and distinctly. Here, again, the general principle of characteristic tracing is employed. The voltage of the generator is applied to the horizontal plates and the anode currents, due to this voltage, produce a drop in potential across the resistance R_a which is applied to the vertical plates of the cathode-ray tube. In order that the characteristic may be correctly evaluated over the whole of its length, it is desirable for it not only to be of sufficient size, but also its central linear portion shall be neither too steep nor too flat. The best condition is obtained when the linear part of the curve is inclined at about 40° to the abscissa axis. In order that the characteristic shall take up the position referred to on the screen, it is necessary for the voltages in the various parts of the circuit to be suitably chosen. First of all, the voltage of

the source must be such that the abscissa occupies approximately half the diameter of the fluorescent screen. Then the voltage divider in question should tap off a portion of the generator voltage so that the characteristic of the valve is fully extended from the starting point up to the saturation point. The resistance of the voltage divider should be kept sufficiently low to prevent grid current, which exists at the instant when the grid is positive, from causing any appreciable voltage drop across this resistance. If the generator has a sine wave voltage —this can be checked immediately with the help of a moving mirror—the effective voltage on the grid of the valve can be determined by the aid of a simple alternating current voltmeter, and in this way the abscissa scale can at any time be ascertained. The length of ordinate necessary for the best position of the characteristic is more difficult to secure. The anode resistance R_a, as previously stated, must be small compared with the internal resistance of the valve. Nevertheless, in order that the voltage drop (one-tenth the anode voltage used) may give sufficient ordinate length, the deflection sensitivity in this direction must be considerable. The pair of ordinate plates must be very long and narrow. Further, low electron velocities in the cathode-ray tube should be used. If the required length of ordinate is not obtained in spite of these precautions, a single stage of direct-coupled amplification should be used at this point. The ordinate scale can also be varied within wide limits by adjusting the anode resistance R_a. Calibration of the ordinate scale is most easily carried out by either a direct current of known value fed through R_a, or by an alternating current of known magnitude. The latter method of calibration is used in the circuit discussed. To calibrate this circuit, it is only necessary to switch over from M to E. By adjusting the resistance R_o it is easy to control the length of ordinate, which has been determined by the anode current of the valve.

The various methods of regulation discussed are necessary if a satisfactory comparison of valves having varied performance is to be made with one and the same testing circuit. The characteristics of various types of valves do not always show such close agreement as the example of Fig. 325. It is necessary, therefore, to be able to alter the range of measurement of the circuit whenever a new type of valve is inserted. A very different state of affairs exists when the

characteristics of the same type of valve are to be observed with the same equipment as, for example, for the purpose of checking manufacture. In such cases, it is simpler to dispense with the ordinate calibration and judge the valve by comparison with a normal one. Simple circuit arrangements for making the characteristics of two different valves visible at the same time have already been instanced and discussed above (Chapter II, Figs. 301–303). Fig. 326 shows the outlines of two different valves in the characteristic comparator.

The magnitude and direction of the grid current for various

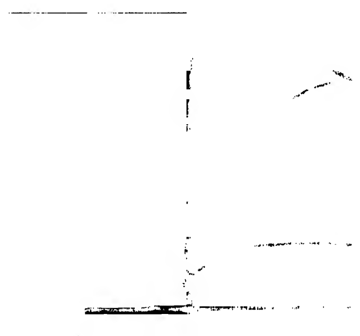


FIG. 325. CHARACTERISTICS OF VARIOUS TYPES OF VALVES

FIG. 326. CURVES OF TWO VALVES IN THE CHARACTERISTIC COMPARATOR

values of grid voltage can be read off directly from the fluorescent screen. To do this, it is necessary to connect a high resistance (about $5\text{–}10.10^6$ ohms) in the grid lead of the valve under examination, the resistance being normally short-circuited.[10] The voltage drop produced across this resistance by the grid current produces a corresponding alteration in the anode current characteristic, which is clearly visible if the short-circuiting contact for this resistance is quickly depressed. Fig. 327 shows an outside view of an equipment for measuring characteristic curves which includes the circuit whose principles have been discussed (Fig. 324). Besides the instruments necessary for calibration, the equipment contains other instruments for the adjustment of the heating circuits, and has been developed entirely for mains operation. When operated from the mains, care must be taken to see that all voltages of the equipment are independent of the mains voltage

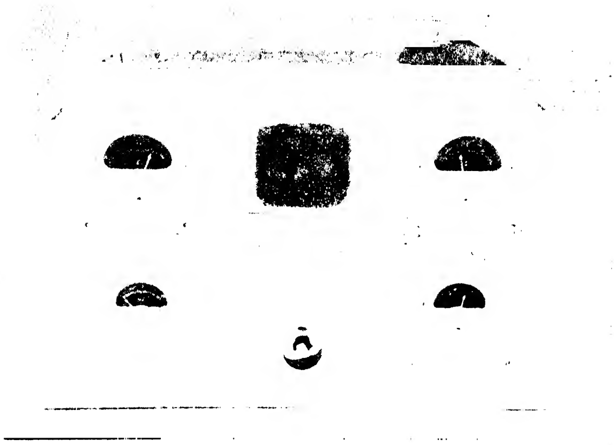


Fig. 327. Front View of an Equipment for Tracing the Characteristics of all Types of Valves

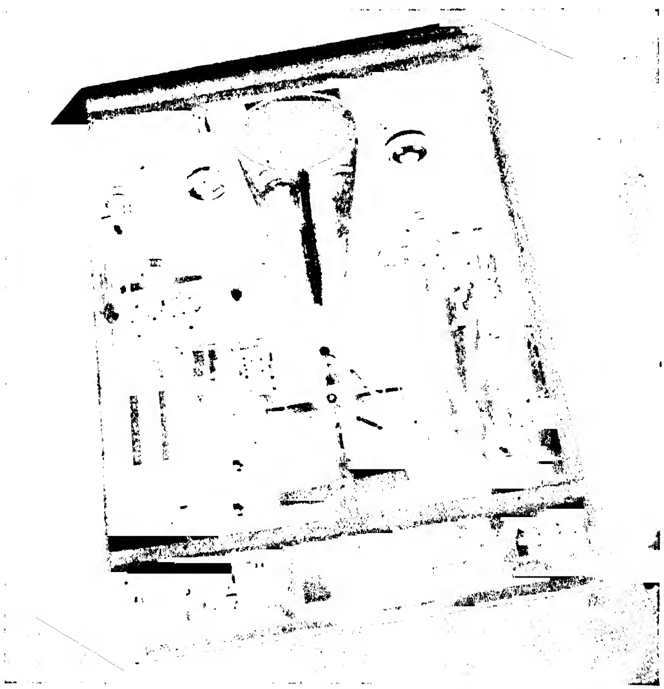


Fig. 328. Inside View of the Characteristic Tracing Equipment

and of changes of load which are caused by the valve itself in the course of its investigation. Fig. 328 is a photograph of the interior of an equipment for tracing characteristics, and constitutes an instructive example of compact mounting of valves and other components of such a circuit. If correctly orientated and placed as far away as possible from the mains transformers, disturbance of the ray is avoided.

Ability to trace the dynamic characteristic taken under working conditions is a special merit of the cathode-ray tube. Furthermore, distortion of the characteristic caused by reaction of the anode current on other parts of the circuit does not

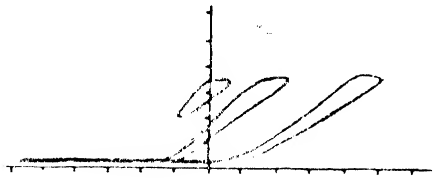


FIG. 329. CHARACTERISTICS OF A MODULATING VALVE

occur. Tracing the dynamic characteristic is particularly useful for finding the value of the saturation current of the valve, the emissive properties of which are completely altered by the superimposition of high anode currents on the heating circuit.

Dynamic characteristics can be traced over the whole frequency range which is covered during operation. The investigation of dynamic characteristics is of particular importance if capacitance, inductance, or even reactances in which both these components occur, are included in the grid or anode circuit of the valve. Fig. 329 shows a typical example of dynamic characteristics with a reactance consisting of resistance and capacitance in the grid circuit of the valve. This shows the relation between anode current and grid voltage for a valve having an external control electrode, which relation cannot be found from static measurements. In spite of a pure ohmic resistance in the anode circuit, the various characteristics

show a phase displacement between alternating grid voltage and anode current which originates through the capacitance between the negative charge on the inside of the bulb—the so-called wall charge—and the control electrode, the impedance of which at a supply frequency of 50 cycles is no longer small compared with the ohmic resistance in the circuit. As the ohmic resistance in this case has the high value of $12 \cdot 10^9$ ohms the above mentioned capacitance could be determined easily from the photograph, its value being 0·8 $\mu\mu$F. in this case. With externally controlled valves, the wall-charge effects, which otherwise can be scarcely traced, cannot be estimated quantitatively until the dynamic characteristics are investigated.

Of course, the tracing of characteristics is not limited to the cases where the anode current is recorded as a function of the grid voltage; the anode current as a function of the anode voltage or as a function of the potential of any auxiliary electrode which may be present can be recorded. In more complicated circuits the apparent capacitance and resistance due to the anode-grid capacitance can be shown under working conditions. Furthermore, characteristics of oscillatory circuits, those which show the magnitude of the first and second differential coefficients of the anode current characteristic, and other curves in similar arrangements, can be produced in a relatively simple way. The tracing of characteristics of discharge tubes is particularly important, since these can be traced without error and under working conditions, showing the influence of static wall charges and other effects.

The examination of grid-controlled gas-discharge tubes, as well as the investigation of the striking mechanism of gas discharge tubes in particular, are further problems for the cathode-ray tube.

Very instructive investigations have been carried out with the cathode-ray tube in tracing oscillograms of the loads which are present under working conditions in high-vacuum, and more particularly gas-filled rectifier valves. A number of other properties of valves can be clarified quantitatively by means of oscillographic methods. For example, it is possible by the aid of the cathode-ray tube, and a calibrated pre-stage amplifier, to ascertain the disturbance due to microphony, a.c. heating of the valve cathode, and finally the Schrot effect, and to estimate their relative importance with reference to the modulation range of the output stage.

(E) EXAMINATION OF AMPLIFIERS. To obtain the characteristics of an amplifier, a knowledge of the degree of amplification at various frequencies over the range it is used is of the greatest importance. If the degree of amplification is determined at one frequency or at a number of frequencies, i.e. point by point, the usual circuit arrangement can be employed and the cathode-ray tube is preferably used as a voltage measuring device. It has considerable advantages over ordinary voltmeters (electrometers, valve voltmeters, etc.), particularly if the circuit is one in which the amplitude of the voltage is sufficient for direct deflection. The observation of the distribution of light on the fluorescent screen or consideration of the shape of the curve with the help of electrical or mechanical time deflection, makes it possible at the outset to determine whether the voltage being measured is sinusoidal. The errors in measurement due to harmonics are consequently removed by using the cathode-ray tube as a voltmeter. Compared with the electrometer, the cathode-ray tube as a potential measuring device has the advantage of being easily inspected and, as compared with the valve voltmeter, freedom from inertia in indication and ease of calibration. The particular advantage of the oscillograph voltmeter in calibration of amplifiers lies in the fact that spurious disturbances are easily recognized and separated from the voltages being measured. If it is only required to determine the maximum amplification, the ballistic method with the cathode-ray tube, already described (Chapter II, page 191 *et seq.*), is very simple to construct and use.

The way in which the frequency affects the degree of amplification can be made visible on the screen of the tube in oscillatory circuits, as well as transformer stages by the method previously described in Chapter II, page 288 *et seq.* To secure correct measurements, care must be taken to see that the source of l.f. vibrations or h.f. transmitter supplies the same amplitude to the amplifier input circuit at all frequencies over the range covered (if necessary, by a voltage divider).

Another important curve of an amplifier is the amplitude characteristic. The relation between degree of amplification and amplitude can be traced in several ways by the cathode-ray tube. As a rule, it is sufficient to determine the relation for the frequency at which maximum amplification occurs. The most convenient method consists in injecting in the amplifier input circuit a voltage of constant frequency but periodically

varying amplitude. The maximum amplitude and its degree of modulation should be selected so that during one modulation period the entire range involved is covered. The greater the difference between the voltage frequency and the frequency of modulation, the more points on the amplitude characteristic will be indicated.

Measurement of amplification under working conditions is carried out in such a way that, for example, the fluctuating input voltage is applied to one set of deflection plates, and the amplifier output voltage is applied to a perpendicular set of plates. With suitable phase adjustment, a fluorescent stroke is produced, which traverses the origin of co-ordinates and whose inclination to the abscissa provides a scale for the degree of

FIG. 330. OSCILLOGRAM OF TWO SUPERIMPOSED SINE WAVE VOLTAGES OF DIFFERENT AMPLITUDES AND FREQUENCIES

amplification. As soon as the linear relation between input and output alternating voltage no longer obtains, the characteristic recorded shows portions of lower slope.

A further method used by the author to show the effect of amplitude variation in aperiodic amplifiers, transformers, and other components where the effect of frequency variation is less marked and the output limited consists in using a symmetrical saw-tooth oscillation, i.e. whose rise and fall is linear and occurs with the same + or — slope. If such oscillations with linear traverse are present at the input side of the unit whose amplitude characteristic is being measured, the oscillogram of the output voltage will show the characteristic amplitude curve directly instead of the original linear traverse over the range of measurement determined by the amplitude of the oscillation. Such saw-tooth oscillations are easily produced with the devices discussed previously (Chapter II, page 266 *et seq.*) if the charging and discharging circuits are suitably designed. The required symmetry and linearity persist if the charging and discharging currents always retain the same value.

The oscillographic process last mentioned for determining amplitude variation can be varied by superimposing a second voltage of considerably higher frequency, and much smaller but constant amplitude, on the voltage to be measured. The reduction in slope of the resulting characteristic of the whole amplifier can be very easily found from the reduction in amplitude of the superimposed voltage. The method has the advantage of not being confined to one particular shape of curve in the measured voltage. Fig. 330 shows an oscillogram of two superimposed sine wave voltages where amplitude and frequency are suitably chosen for the investigation of amplitude variation. The distortion of the outline of such a curve as a result of variation in amplitude is shown in Fig. 331. The

FIG. 331. SUPERIMPOSED SINE WAVE VOLTAGES OF DIFFERENT AMPLITUDES AND FREQUENCIES DISTORTED BY OVER-MODULATION

negative half-cycle of the fundamental covers a range where the degree of amplification is very much reduced. The result is that the small superimposed voltage in this region almost disappears. Although the methods for amplitude measurement so far mentioned furnish fairly accurate results, even if the resulting amplitude curve is of a complex character due to several sources of distortion, the following extremely simple method is used, and provides information about the modulation range if this is limited in any way.

In most cases, amplitude restrictions result from the limited modulation range of its last stage. In practice, this range is generally limited by the existence of grid current and by the upper as well as the lower bend of the curve.

If voltage swings exceed these extremes, severe distortion occurs as shown upon the oscillogram. The distance between the upper and lower limit is a measure of the load which the amplifier can deal with. The oscillogram of a low-frequency oscillation, the amplitude of which is over modulated during the greater part of the time, is shown in Fig. 332. It can

be seen from this illustration that the oscillation amplitude is sharply limited by the upper and lower limit of the modulation. Fig. 333 shows as a comparison the oscillogram of an

FIG 332 OSCILLOGRAM OF AN L F OSCILLATION DISTORTED BY OVER MODULATION

undistorted low-frequency oscillation. The oscillographic control of the modulation in amplifiers, Kerr cells, glow lamps, gramophone disc recorders is among the most important of

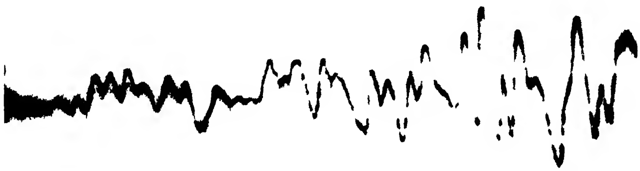


FIG 333 OSCILLOGRAM OF AN UNDISTORTED L F OSCILLATION

the uses of the cathode-ray tube. The operating range is usually shown by markings on the screen of the tube. As soon as the voltages exceed these positions, volume controls are used to reduce the amplitude to the maximum permissible value. Frequently, a 50-cyc. voltage taken from the lighting mains is used as a time deflection in such measurements of modulation.

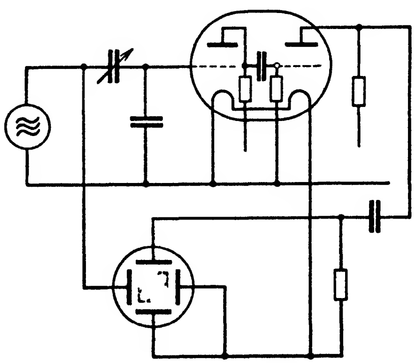


FIG. 334 MEASURING CIRCUIT FOR DETECTION OF PHASE DISPLACEMENT IN CASCADE AMPLIFIERS

In certain problems, information of the phase change produced by an amplifier at various frequencies is important. Particularly is

this the case with respect to reaction and reactive coupling in amplifiers which are used for optical and not acoustic reproduction, and with amplifiers used in conjunction with cathode-ray tubes in measuring equipment. A simple circuit arrangement for determining phase changes in cascade amplifiers is shown in Fig. 334. Exactly as in the case of the arrangement mentioned on p. 382, the input and output voltages are applied to both pairs of plates of the cathode-ray tube. The capacitive voltage divider shown, which has no effect on the phase relation, allows the input voltage to be adjusted so that the output a.c. amplitude reaches the amplitude of the generator voltage.

The result of phase measurement in a h.f. dual valve is shown

28 000 m. 2 500 m. 230 m.

FIG. 335. PHASE DIAGRAM OF A H.F. AMPLIFIER

in Fig. 335. The unit under examination shows from the frequency curve that its maximum amplification is reduced to one-half that at wavelengths of about 230 metres and about 28 000 metres. Agreeing well with theory, the phase diagrams shown depict a circular shape at the above mentioned limiting wavelengths. At the frequency at which maximum amplification occurs (2 500 metres in the unit in question) a straight line appears, since the input and output voltages are in phase. This example shows the great advantage of well-designed resistance coupled amplifiers in which phase changes over wide frequency ranges near the resonance frequency are small enough to be ignored.

Another field of investigation which depends to a large extent on the cathode-ray tube is the oscillography of the process of switching on amplifiers. If an impulse is communicated to an amplifier unit it appears after a very short lapse of time at the output side of the amplifier. The slope of the

voltage rise is at the same time very considerable and depends on the upper frequency limit of the amplifier. With h.f. or television amplifiers, the rise occurs in a period of about 10^{-5} to 10^{-6} sec., i.e. in a time which corresponds nearly to the upper frequency limit of the amplifier. The voltage drop then starts comparatively slowly. The time required for the drop agrees with the period corresponding to the lower frequency limit of the amplifier. For telephony amplifiers it is of the order of $\frac{1}{20}-\frac{1}{100}$ sec. Whereas the slower of these changes can be easily photographed in one traverse, the more rapid one needs to be repeated a number of times in order that such

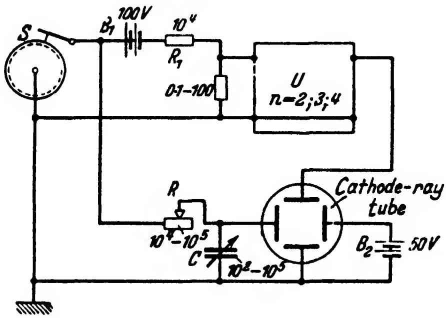


FIG. 336. CIRCUIT FOR MEASURING TIME OF SIGNAL TRANSMISSION THROUGH AN AMPLIFIER

a record can be obtained when using a low-voltage tube. Fig. 336 shows a simple arrangement for investigating the process of switching on, with low-voltage tubes. The principle of this arrangement consists of comparing the time taken for the transient to build up with the time constant of a fixed resistance-capacitance circuit, the discharge of which is responsible for the tracing of the time axis of the cathode-ray tube, while the transient under examination is shown against the vertical axis perpendicular to it. The difficulty consists in starting the two processes at the same instant. In the circuit arrangement illustrated, this difficulty is overcome by controlling both circuits by a single switch. A battery of about 100 volts having a low internal resistance is earthed through an ohmic resistance R_1 which has a total resistance of 10^4 ohms. From this divider a voltage of 10^{-3} to 1 volt is tapped off according to the sensitivity of the amplifier A to be investigated. The positive pole of the battery is permanently

connected to the measuring condenser C and the time axis pair of plates of the tube. When the switch S is open, the battery charges the condenser C through the resistance R, the fluorescent spot being predeflected to one end of the time axis. As

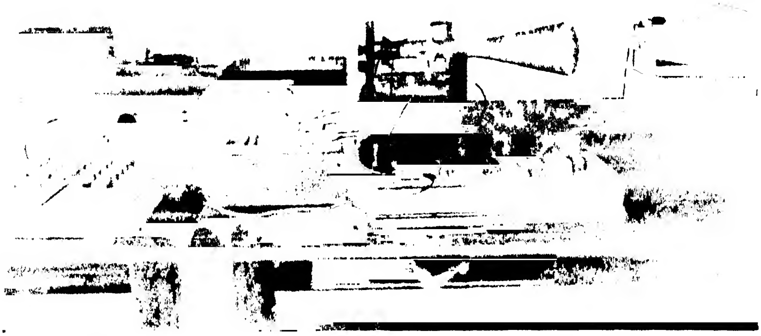


FIG. 337. VIEW OF THE ARRANGEMENT FOR INVESTIGATION OF THE PROCESS OF SWITCHING ON AN AMPLIFIER

soon as the switch S is closed, the condenser is discharged to earth through the resistance in a period of time which is known exactly. At the same time, the fluorescent spot is carried

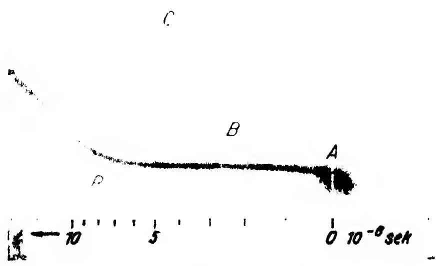


FIG. 338. TRANSIENT AT THE MOMENT OF SWITCHING ON IN A FOUR-STAGE R.C. AMPLIFIER

to the other end of the line by a battery B_2 of about 50 volts. Simultaneously, however, a voltage impulse reaches the

amplifier through the switch S. The desired range of the oscillation curve can be adjusted on the screen by varying the time constant of the time deflection system. The switch S which is constructed as a rotary interrupter is designed so that the times of opening and closing are long compared with the times of the events taking place in the circuit. Fig. 337 illustrates an experimental arrangement similar to that described. The rotary switch is in the left background. At the rate of 30 interruptions per sec. and with exposures of about 5 min. photographs could be taken with the ordinary tube which enables times of 10^{-6} sec. to be recognized satisfactorily. Two

FIG. 339. SWITCHING OFF TRANSIENT IN A FOUR-STAGE AMPLIFIER

typical oscillograms are reproduced in Figs. 338 and 339. Fig. 338 represents a transient in which the duration of the transfer in the amplifier B, the building-up period C, and the attainment of the maximum D can be recognized. Fig. 339 shows a transient in which the fading time of the pulse is relatively large, in which the rising curve of the previous illustration is visible only as a weakly illuminated portion A compared with the very much more marked portion B, which is the fading portion of the pulse. The oscillograms shown were taken from a 4-stage resistance coupled amplifier in which the degree of amplification at 30 cyc. and 20 000 cyc. has fallen to half its maximum value. According to their mode of formation, both these oscillograms are cyclic and the very bright return traverse line R and the origin A had to be specially shaded to prevent overloading the screen. The measurements

given here were obtained with an old type gas-filled tube. A modern high-vacuum tube would trace both curves with excellent definition. The procedure for investigating of switching-on processes in amplifiers has been discussed in detail in this chapter because, with slight alteration, it can be applied to investigating various processes involved in work with overhead lines, cables, filters, and other units.

(F) EXAMINATION OF RECTIFIERS. Rectifier circuits are used in high-frequency technique in the mains units and in the receiver itself for the rectification of high-frequency voltages fed into it. The methods of examination of the two chief groups of rectifiers differ considerably owing to the great difference of output and frequency range involved. First, we will discuss the methods for examination of rectifiers for supply from lighting mains. The oscillographic method used for investigating hot-cathode rectifier arrangements has already been given previously (Chapter III, page 374 *et seq.*) The oscillographic method is also to be recommended for the investigation of electrolytic and metal rectifiers. In view of the comparatively low frequency which is usually involved, all details of the curve, for instance, as in the case of detecting asymmetry in full wave rectifier circuits, the magnitude of reverse current, determination of current and voltage curves at the rectifier, can be observed when the reservoir condensers, rectifier load, and voltages at the rectifier, are given different values. As has recently been shown,(11) however, it is scarcely possible with loop oscillographs to produce a curve whose outline is entirely free from distortion even with the rectification of 50 cyc. or 100 cyc. a.c. The examination of fluctuating d.c. produced by rectification will be discussed in detail later in Chapter III, page 366 *et seq.* In combination with suitable voltage dividers (Chapter II, page 211 *et seq.*) it is possible to examine with a low-voltage tube the current and voltage curves at the rectifier portion of the equipment.

The oscillographic method is also suitable for rectifiers used with receivers in which the primary object is to estimate the nature and magnitude of the distortion in the rectifier, and to ascertain the sensitivity of the arrangement. Clear information can be obtained from the deviation of the curve outline which can be observed from the resulting low frequency compared with the low frequency which modulates the high frequency. These data, however, unfortunately are valid only for one set

of conditions, i.e. for the particular receiver and rectifier used and for the high-frequency amplitude involved. Even small changes in the h.f. amplitude are sufficient to alter the outline of the curve considerably. In spite of this, the oscillographic method has its uses even in the examination of receiver rectifier combinations. Only the oscillogram of the low frequency in the anode circuit of the rectifier, or from the output of a subsequent amplifier, will show whether the high-frequency components have been sufficiently removed. The proportion of h.f. which produces distortion and characteristic reaction disturbances, makes itself apparent in the oscillogram through a thickening of the outline of the voltage tracing. The symmetrical time discharge circuit discussed in the last section can be used for the investigation of rectifier units which are independent of frequency. If the internal resistance of the source of the time discharges is small compared with the minimum input resistance of the rectifier unit, then the oscillogram of the output voltage will show directly the resistance characteristic of the rectifier. The process described below is more suitable for the examination of receiver rectifiers, and takes into consideration the effect of all frequencies. In order to obtain data which, as far as possible, are characteristic of the rectifier, it is advisable to use a method which discloses the complete characteristics of the unit. That characteristic which shows how rectification depends on applied voltage gives comprehensive information about the rectifier. In all cases the rectifier characteristics have a square form at their lowest portion. A linear portion generally starts above 0·5–1 volt with a.c. In many cases the characteristic bends back in its upper portion. When the rectifier characteristic is known, the most favourable h.f. voltage should be taken from the linear portion, and also the highest degree of modulation permissible at this h.f. voltage. If the l.f. amplifier is adjusted to the optimum h.f. voltage of the receiver-rectifier unit, then all stages of the receiver are properly designed.

In most cases the dynamic method of curve tracing with cathode-ray tube is the only one which supplies data corresponding to the actual working conditions. Static methods often give incorrect values, as they do not take into consideration the effect of variation in frequency. Even the dynamic method of tracing rectifier characteristics with alternating voltages and valve voltmeters seldom give data free from

errors, as the valve voltmeters show considerable error due to the distorted voltages which invariably occur. A circuit for tracing rectifier characteristics(12) with the cathode-ray tube is

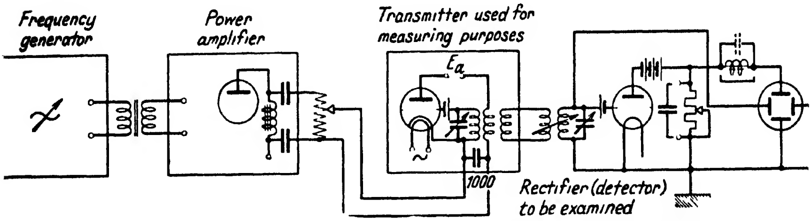


FIG. 340. CIRCUIT FOR MAKING VISIBLE THE CHARACTERISTICS OF RECEIVER DETECTORS

shown in Fig. 340. An essential condition involved in this method is that the h.f. input voltage must swing sufficiently rapidly between zero and its maximum value. Such a h.f.

FIG. 341. OSCILLOGRAM OF A H.F. OSCILLATION VERY STRONGLY MODULATED FOR THE PURPOSE OF PHOTOGRAPHING THE CHARACTERISTIC

voltage can be very easily produced by modulating a transmitter to such an extent that the amplitude of oscillation periodically falls to zero. This can be secured by anode voltage modulation of a small measuring transmitter with the assistance of an efficient audio-frequency generator power amplifier combination. The oscillogram of a strongly modulated h.f. voltage obtained in this way is reproduced in Fig. 341. The principle of the method consists in applying the modulated high frequency to the horizontal plates of the cathode-ray tube and the low frequency after rectification to the pair of plates at right angles. The shape of the curve of the modulated l.f. oscillation is not of any great importance. It only alters the distribution of brightness on the resulting image. As the h.f. and l.f. voltages are linked together in conformity with the laws of rectification, the latter must appear in the circuit

discussed as a fringe to an illuminated surface. If a low frequency of more than 30 cyc. serves as a modulating frequency, then the figure will appear as a stationary luminous

FIG. 342. THE RECTIFIER (DETECTOR) CHARACTERISTIC AS THE EDGE OF A LUMINOUS SURFACE

one. Distortions which occur during the operation of the rectifier can only be avoided as long as there is a linear relation between rectification and h.f. voltage. As an example, a particularly bad rectifier characteristic obtained in the manner discussed, is illustrated in Fig. 342. Only comparatively short portions of this characteristic can be regarded as approximately linear. The highest permissible degree of modulation which is possible without distortion can be read off the characteristic figure. Fig. 343 shows how it is possible to do this. Let the high frequency be indicated by the amplitude A_1. Then, according to the construction of Fig. 343, let a perpendicular from the point B, where the curved and linear portions of the rectifier characteristic meet, fall on to the ordinate. The amplitude A corresponding to the length of this perpendicular makes it possible to determine the maximum degree of modulation which is $K = (A_1 - A)/A_1$. Therefore, in the most favourable case (power detection), shown by this construction, the maximum degree of modulation

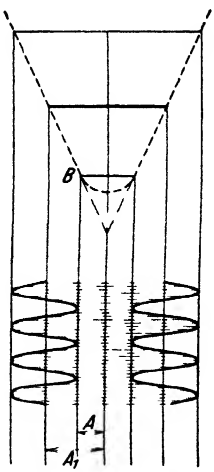


FIG. 343. DETERMINATION OF THE DEGREE OF MODULATION FROM THE DETECTOR CHARACTERISTIC WHICH SHOWS THE LIMIT OF UNDISTORTED RECTIFICATION

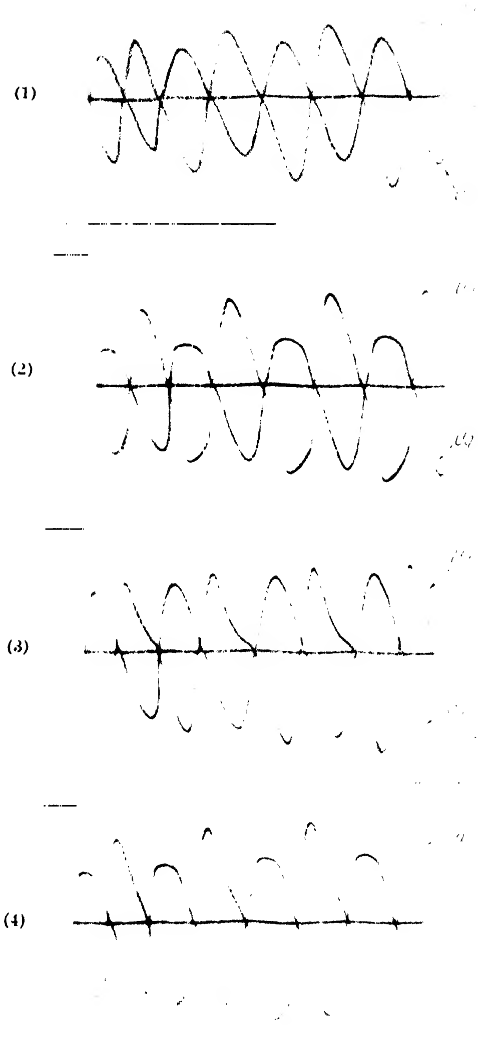


Fig. 344 Grid and Anode Voltage Curves under Varied Voltage Conditions (Valve RE604)

(1) Outline of voltage for correct point of operation without excessive modulation
(2) Outline of voltage when bias is too low (distortion caused by grid current)
(3) Outline of voltage when bias is too great
(4) Outline of voltage when over-modulated

amounts to about 60 per cent. In the rectifier characteristic of Fig. 342, the maximum permissible degree of modulation is, however, only about 20 per cent. Rectifier curves which follow more complicated laws can be ascertained with the arrangement described in receivers in which the receiver rectifier acts in an unusual manner as an anode, as well as a low-frequency rectifier. By superimposing the opposed rectifier effects, characteristics are produced which show low sensitivity and permit of low modulation.

(G) Examination of Output Stages. Earlier in the present chapter the tracing of oscillograms of amplifier output alternating voltages was recommended in order to record the effect of overloading. This practice is particularly applicable to the investigation of output stages, where the voltage amplitude reaches the highest values in the anode as well as in the grid circuit. Grid and anode voltage curves of an output stage (valve RE604) are shown in Fig. 344 (measurements by Kammerloher) under varied voltage conditions. A well-shaped curve has been obtained only in the top illustration by a correct position of the operating point and absence of excessive modulation. The next oscillogram illustrated shows the distortion of anode and grid voltages which takes place when there is insufficient negative grid bias; these are due to the sudden establishment of grid current. Distortion of the anode voltage curve which occurs as a consequence of too high a negative bias is shown in the next oscillogram, while the lowest one indicates the outline of both voltage curves with overloading. Here, the various types of distortion previously mentioned are superimposed on one another. If measurements such as those previously described are made on a circuit whose subsequent voltage and current performance can be controlled, and the resistance of the anode circuit behaves as a loudspeaker, the maximum permissible output of the last stages can be determined. Fig. 345 shows a circuit used by Kammerloher[13] for this purpose. Measurement of voltage is made either in two different cathode-ray tubes or in one and the same tube, the ordinate plates of which can be switched over from the anode to the grid circuit as desired. The curves shown in Fig. 344 were obtained with this circuit, and a type RE604 valve. In this the sinusoidal voltage of an audio-frequency generator is applied to the terminals, 1, 2, at the voltage divider S, of which the resistance of the portion in the circuit must be of the

same magnitude as the value which is usual for grid leaks of output stages. The a.c. grid voltage v_g is measured either by means of a voltmeter or by the cathode-ray tube itself. This also applies to voltage measurements in the anode circuit. A.c. measurements in the anode circuit are made at the resistance R_1, which is only about 10 ohms and can be disregarded as introducing any disturbance. The anode a.c. resistance consists of a choke, the inductive effect of which is entirely shorted by

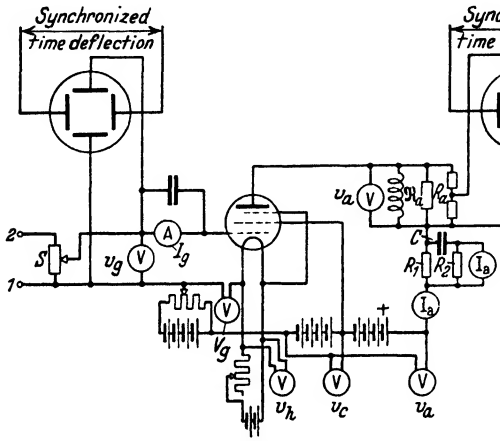


FIG. 345. CIRCUIT FOR ESTIMATING OUTPUT AT THE FINAL STAGES

the ohmic resistance R_a at the frequency of measurement. In the measurement of single grid valves the connexions to screen and suppressor grids are dispensed with. The anode a.c. output can always be calculated from the measurements of the anode alternating voltage and current. The corresponding values at the most favourable operating point before distortion sets in gives the maximum output for the valve in question, and for the conditions of voltage and anode resistance existing at the time.

For different investigations of output stages it is useful to make dynamic operating characteristics visible. The portrayal of the characteristics can be made with the same circuit arrangements as have already been discussed in earlier chapters (Chapter II, page 287 *et seq.*, and Chapter III, page 374 *et seq.*). In such cases the tracing of the characteristic is particularly easy since in examination of the last stages a.c. voltages of ample magnitude are available, and the use of auxiliary amplifiers is

quite unnecessary. It is usual to trace the operating characteristic with a sinusoidal voltage. The characteristic which then results is the dynamic one for the particular frequency of the sine wave voltage. An interesting variation consists in tracing the operating characteristic directly by l.f. voltages with the complicated outline which occur in practice, instead of using sinusoidal voltages. The fluorescent image which is produced shows the intermixed operating characteristics running into one another, their position, shape and magnitude depending on the amplitude, frequency and components of the l.f. oscillation. The brightness distribution of a group of curves obtained in this manner furnishes a statistical survey of the actual demands made on the last stages during working conditions. If the last stage is overloaded, very sharply-defined limits of the illuminated surface will show the position where grid current starts. Valuable data for the investigation of output stages in combination with loudspeakers can be obtained by photographing tracings with sinusoidal voltages of operating characteristics for various mechanical acoustic conditions of the loudspeaker. For freely suspended and fixed loudspeaker coils, dynamic curves of the final stage of a loudspeaker with overloading and excessive inductive loading of the anode circuit are given in Fig. 346.

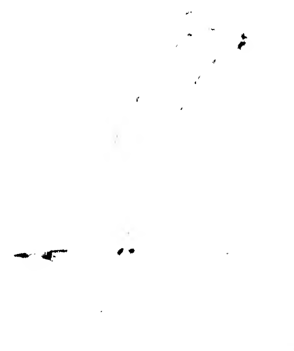


FIG. 346. CURVE OF THE LOUDSPEAKER OUTPUT STAGE UNDER WORKING CONDITIONS WITH FREELY SUSPENDED AND FIXED COILS

(H) MEASUREMENTS ON LOUDSPEAKERS. From the changes which can be observed in the operating characteristics of output stages when a loudspeaker membrane is coupled to the oscillating system of the speaker, when the loudspeaker is placed in a room under increased or reduced air pressure, when funnels or acoustic screens are used or varied when moving parts are made fixed in position, when the restoring forces are altered, and when the mechanical transmission links are varied, the most important values of the arrangement constituting the electrical substitution of the

loudspeaker can be determined. The effect of the changes indicated are even more clearly expressed by the voltage/current characteristic of a loudspeaker. This characteristic can be obtained quite simply when using an output valve of low impedance, by applying the voltage to the horizontal plates and the current deflection in the perpendicular direction. With relatively high currents, it is expedient to carry out the current deflection magnetically. A characteristic obtained in this way is shown in Fig. 347. The loudspeaker should be considered as an ohmic resistance only over a narrow

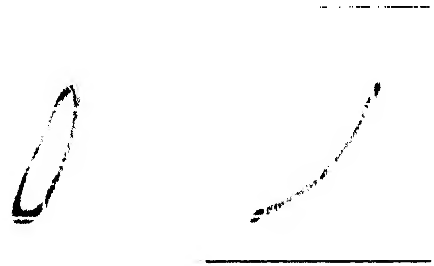


FIG. 347. CURRENT-VOLTAGE CHARACTERISTIC OF A FOUR-POLE MAGNETIC LOUDSPEAKER (FREQUENCY 100 CYCLES WITH EXCESSIVE DISTORTION)

frequency range in the vicinity of its point of electrical resonance (1 000–2 000 cyc. with the usual type of magnetic speaker). In order to obtain an open curve instead of an elliptic characteristic, even in other frequency ranges, it is necessary to compensate the phase displacement of current and voltage by means of a phase-shifting device. Fig. 347 shows on the left, the characteristic without, and on the right, with the phase shifting device. The non-linear nature of the characteristic is well defined in the illustration. In these measurements, a four-pole magnet loudspeaker was used at a frequency of 100 cyc. which is comparatively low for a speaker of this type. The change in the characteristic in respect of the factors mentioned above is particularly instructive for variation of frequency. Of course, the phase displacer must be readjusted to the frequency each time. In addition, the method described takes account of the effect of parallel capacitances and varied ratios of turns from the output transformer.

A problem involving measurement which arises frequently is the estimation of the acoustic output of the loudspeaker in

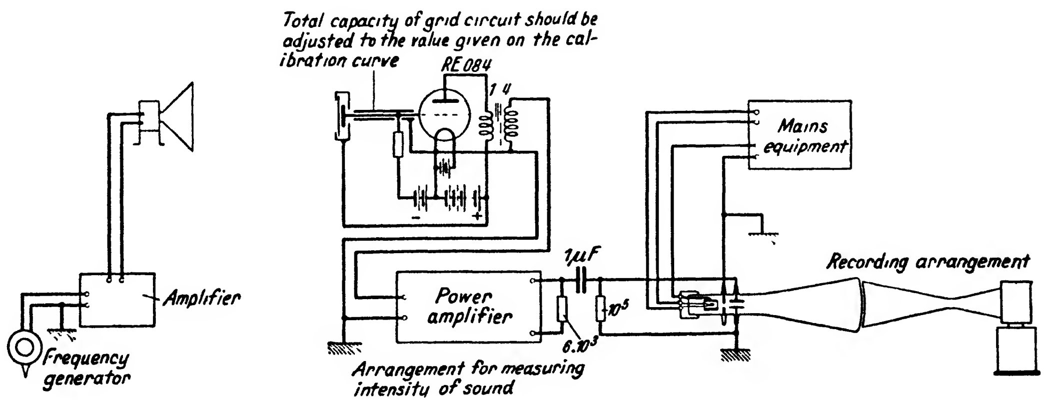


Fig. 348. Diagram of a Simple Arrangement for Measuring in Comparative and Directional Tests

relation to frequency when the alternating grid voltage at the final stage is constant. For all cases where only comparative measurements are required, it is sufficient to place opposite the loudspeaker a microphone with a flat frequency response with an attendant amplifier, and to determine the way in which the output voltage of the amplifier varies with the frequency. The simple arrangement in question is shown in Fig. 348. Here an amplifier serves as an audio-frequency generator and the input voltage of this is supplied by a frequency record (see next section) through a pick-up which, if possible, should have a response characteristic which is independent of frequency. By using a variable frequency standard, the frequency may

FIG. 349 RECORDED FREQUENCY CURVE OF AN OLD TYPE OF DYNAMIC LOUDSPEAKER

be altered from the highest to the lowest pitch. Frequency change relative to time is so arranged with most disc records that the same space of time is required for a frequency range covering one decade, so that recording takes place uniformly and the abscissa scale is automatically divided logarithmically on the sound receiver side. The recording of the voltages on the output side of the receiver can be best carried out with the aid of a cathode-ray tube and a recording device (Chapter II, page 328).

The substitution of a cathode-ray tube for a recording instrument has the advantage that by reason of the linear time scale, a greater amplitude interval is recorded and errors due to harmonics are absent. Fig. 349 shows a recording of an older form of dynamic loudspeaker obtained with this simple arrangement. If the loudspeaker and microphone face each other in the open or in a room from which echo effects are removed by a special covering on the walls, i.e. if no form of stationary waves can be produced, then the recording has the added

advantage that non-linear distortions are clearly shown, and can be recognized from the outline. By varying the shape of the curve at the various frequencies by means of time deflections, amplitude distortions are immediately visible and are not complicated by echoes. If it is intended to investigate the outline of the sound vibrations produced relative to frequency, then it is necessary to see that the voltages applied to the last stage have sinusoidal outlines and that overloading of the output stage itself does not take place. The audio-frequency generator shown in Fig. 348 is replaced by an audio-frequency oscillator with low coefficient of non-linear distortion.

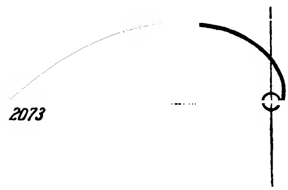


FIG. 350. SHAPE OF SPECIAL CONDENSER PLATE

A great deal has already been written concerning audio-frequency oscillators.

If automatic recording is required when an audio-frequency generator is used. efforts should be made to secure a logarithmically divided frequency scale. This can be accomplished if a particular shape. depending on the conditions of the case, is given to the condenser controlling the frequencies of the oscillator. The shape of the frequency condenser which was calculated for an

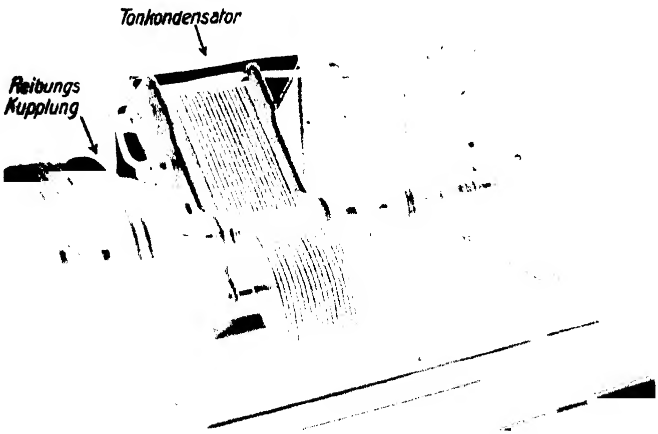


FIG. 351. LOW-FREQUENCY CONDENSER WITH TRIMMER AND COUPLING ARRANGEMENT

Tonkondensator low frequency condenser. Reibungskupplung – friction coupling. Korrektionsplatte = trimmer. Schaltkontakt = switch contact.

audio-frequency interference generator, described in detail elsewhere(14), and which is approximately suitable for ordinary generators of this type, the design of which is subject to some variation, is illustrated in Fig. 350. On account of edge effects which in theory are difficult to estimate, an accurate frequency curve will only result when a small condenser or trimmer is connected in parallel with the main condenser which has the required plate shape. Fig. 351 illustrates the

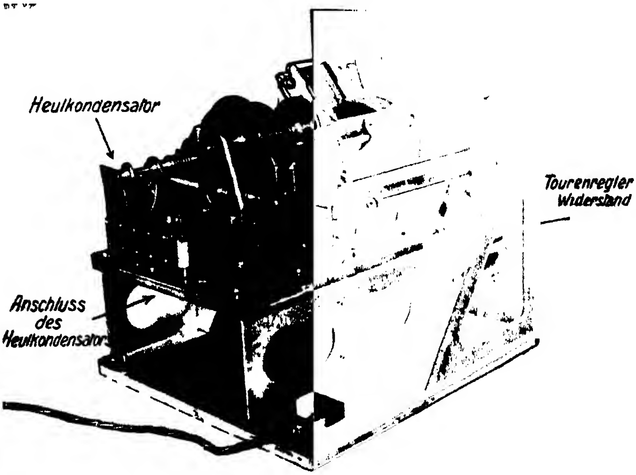


Fig. 352. Side View of Low-frequency Condenser Unit

Heulkondensator warble tone condenser
Anschluss des Heulkondensator connection to the warble tone condenser
Tourenregler Widerstand rotary adjusting resistance

construction of the frequency condenser. The trimmer is visible on the right-hand side. An arrangement of contacts enables the audio-frequency signal to be interrupted for a short period in order to obtain a frequency scale on the record. After the friction coupling is brought into action, the rotary condenser is made to turn round slowly, being driven by a motor. The time taken to cover the frequency range of 50–12 000 syc. is normally 4 min., so that well-defined resonance points are quite sharply outlined. Fig. 352 shows a side view of the frequency condenser with drive and coupling arrangements. For recording frequency characteristics with definite resonance points the accessory equipment for providing slow change of frequency automatically in the audible range

is of the greatest importance. For instance, by its use the pronounced effect of frequency on loudspeaker movements with the membrane removed can be thoroughly investigated. The amplitude of vibration at various parts of the driving system can be determined very easily by the capacitive method above, without the dynamic conditions of the system being in any way altered.

As at the same time, the outline of the amplitude is followed by the cathode-ray tube, the causes of loudspeaker distortion can be picked out.

The cathode-ray tube as a non-integrating system is scarcely suitable for measurement of the coefficient of non-linear distortion, i.e. the estimation of the effective value of the sum of the harmonics to the effective value of the fundamental. On the other hand, by its use, the amplitude coefficient which is the relation of the highest occurring amplitude of all the upper harmonics to the amplitude of the fundamental can be measured satisfactorily. Fig. 353 shows an arrangement for making such measurements. The distorted sinusoidal voltage to be investigated comes directly to one pair of plates, and to the other pair the signal is fed through the amplifier-oscillatory circuit combination. The coupling between the resonant circuit and the amplifier is loose so that the oscillatory circuit shows but slight damping. It is tuned to the fundamental oscillation of the voltage under investigation. The degree of amplification should be adjusted so that the fundamental and the distorted voltage have the same amplitudes. A straight line will then appear inclined to the abscissa axis at an angle of 45° if the voltage measured is free from disturbance. If the measured voltage contains harmonics, then displacements in the direction of the ordinates will appear and the magnitude of the coefficient of non-linear distortion can be read off from the relative values of the amplitudes of the harmonic and fundamental.

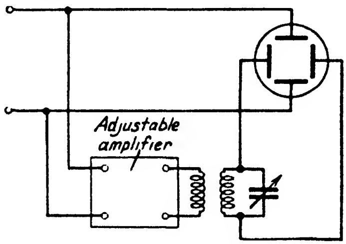


FIG. 353. CIRCUIT FOR MEASURING THE VALUE OF THE COEFFICIENT OF NON-LINEAR DISTORTION

If the whole of the acoustic output of a loudspeaker is to be measured in relation to its frequency characteristic, it is best to use E. Meyer's method.[43] It will be necessary to have a

reverberation chamber, the echo period of which is exactly known at various frequencies, and a source of slightly fluctuating audio-frequency, so that the effect of stationary waves in the room may be eliminated. A method for determination of the echo times in rooms is given in the chapter on the use of the cathode-ray tube in acoustics. The periodic frequency variation is obtained most simply by connecting in parallel with the audio-frequency generator condenser an additional and smaller rotary condenser, one of whose sets of plates is

FIG. 354. THE CATHODE-RAY TUBE AS AN INTERMITTENT LIGHT SOURCE FOR STROBOSCOPIC INVESTIGATION OF MEMBRANE OSCILLATIONS

connected to the axis of the driving motor, and passes the opposite plates at a rate of about 10 times per sec. This condenser, which in view of the characteristic frequency change it produces. is termed a *warble-tone condenser*, can be recognized in the left foreground of the side view in Fig. 352.

An interesting application of the cathode-ray tube in loudspeaker investigations, but one which is limited to tubes with powerful beams, consists in employing the tube as an intermittent light source for stroboscopic investigation of vibrating membranes and movements of a similar kind.[15] In order that the stroboscopic image may be sharply defined, the illumination must persist only for a fraction of the time of one period. An experimental apparatus for use as an intermittent light source is illustrated in Fig. 354.

Two voltages of equal amplitude but differing in phase by 90° are supplied by an audio-frequency generator which also drives the loudspeaker under test, so that a circular figure appears on the screen of the cathode-ray tube. The ray output should be adjusted to be as large as possible, likewise the amplitudes of the deflecting voltages so that the circular figure covers as large an area as possible, and that the fluorescence during operation will not be reduced by saturation phenomena. The resulting circular figure is masked and only a small sector of about 5°–10° remains open to allow the passage of light for illumination. If the after-glow of the screen is less than 10^{-5} sec., then the requirements for carrying out stroboscopic investigations over the whole range of l.f. oscillations are fulfilled. The phase of the illuminated portion can be adjusted as desired by turning the sector round. Perfect synchronism between illumination and the oscillatory motion is obtained by means of the drive from the common generator. Further, with the assistance of neon lamp time discharge circuits, previously discussed, it is easy to obtain intermittent light sources which are easily synchronized. In this case, either the luminous phenomena which are caused by the short time discharge impulse flowing through the neon lamp, or the discharge current itself, is employed to control luminous tubes or light relays. Relatively high illuminations can be obtained in this way if, by means of the brightness control electrode, a modern high-vacuum tube is made to light up periodically. In this connexion, sound-film recording tubes which have a line source of illumination may be specially mentioned.

(I) Examination of Pick-ups. In order to characterize a pick-up, it is necessary to know what voltages are produced at the various frequencies with constant or given velocity amplitude at the needle point. Besides the frequency curve, the coefficient of non-linear distortion which exists at various frequencies must be known in order that a final judgment may be made of the magnitude of the distortions which occur in the pick-up. A measurement which portrays the two factors mentioned, and so shows their effect on quality and efficiency, can be made by the recording method already described (Chapter II, page 328). Fig. 355 shows the complete circuit for recording pick-up characteristic curves. By operating the key T, a d.c. impulse of definite magnitude can be given for

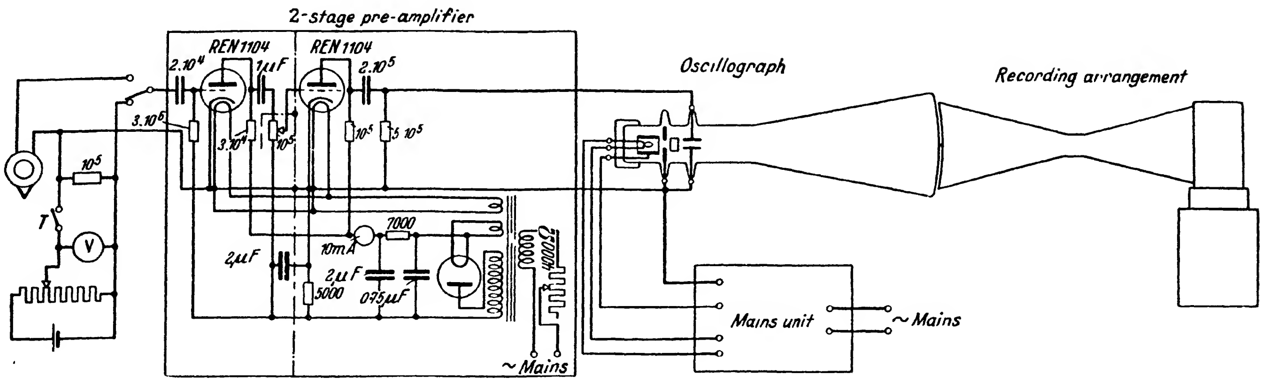


Fig. 355 Arrangement for Recording the Curves of Acoustic Pick-ups

The circuit to the left of the pre-amplifier shows the equipment for producing voltages of known magnitude

calibration of the ordinate scale. It is of great importance to the quality of the registration that the frequency record used

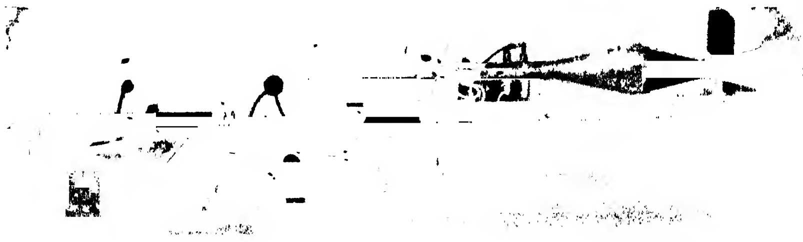


Fig. 356. View of Apparatus for Examining Pick-ups

should be cut with a velocity amplitude which is as constant as possible and, as far as possible, has a sinusoidal wave form.

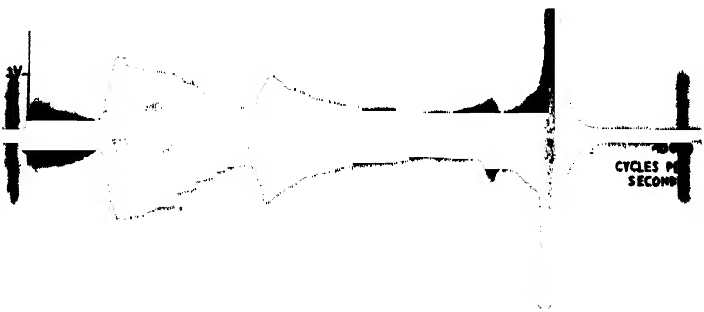


Fig. 357. Curve of a Poor Acoustic Pick-up having Insufficient Damping

The construction of a measuring apparatus embodying the circuit of Fig. 355 is shown in Fig. 356. The turntable, which is driven by a synchronous motor, is arranged on the left, and on the right is the key for the calibration voltage and the amplifier. Then follows the cathode-ray tube with mains equipment and recording apparatus. A record of an inferior pick-up, taken with the apparatus described and showing insufficient damping of the supports, is reproduced in Fig. 357. A further record which shows an excessive number of harmonics over the

entire frequency range is shown in Fig. 358. The excessive production of harmonics is due to the fact that the pick-up is too lightly held, and therefore jumps about in the groove.

FIG. 358 RECORD SHOWING FORMATION OF STRONG HARMONICS OVER THE WHOLE FREQUENCY RANGE (TOO LIGHTLY SUPPORTED PICK-UP CAUSING JUMPING IN THE GROOVE)

Fig. 359 illustrates the record of a particularly good pick-up. Here, the performance is practically independent of the frequency in the particular range 100- 6 000 cyc. Furthermore,

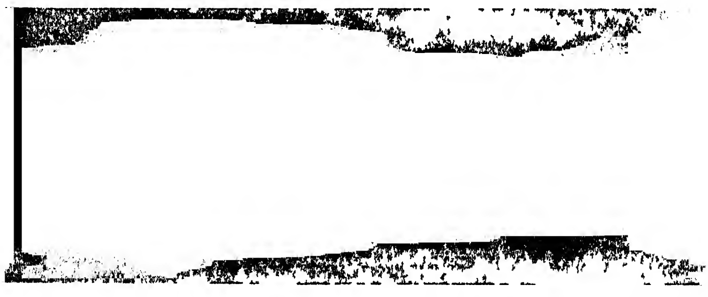


FIG. 359 RECORD FROM A PARTICULARLY GOOD ACOUSTIC PICK-UP

a good shape for the curve has been obtained over the whole of this range owing to the light suspension of the movement. Non-linear distortion only appears at very high frequencies, and needle sag is the cause. The method of recording described enables instructive comparisons of commercial pick-ups to be made. In addition, the method supplies precise information about voltage drop when the needle wears, on the effect of various volume controls, on the frequency

characteristic, on the effect of damping, and on the influence of the weight of the pick-up, etc. These factors have already been reported in an earlier work[16] with records obtained by the methods described as a basis. Besides investigation by record-

FIG. 360. OSCILLOGRAM OF A NOTE WITH NEEDLE SCRATCH SUPERIMPOSED

ing, the oscillographic method is particularly important when the amplitude relation between voltages due to needle scratch and the final modulated l.f. load is to be determined. Fig. 360 shows an oscillogram of a periodic voltage with needle scratch superimposed. The amplitude of the latter in the upper curve

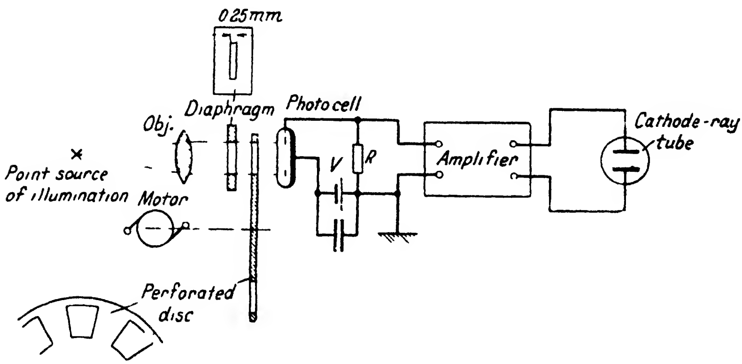


FIG. 361. ARRANGEMENT FOR THE EXAMINATION OF PHOTOCELLS WITH THE OSCILLOGRAPH

amounts to several per cent of the l.f. oscillation and about 1 per cent in the lower curve.

(K) EXAMINATION OF PHOTO-CELLS AND NEON LAMPS. A

knowledge of the properties of photo-cells is of considerable importance especially for television work, also for sound films and many problems involving measurement. The use of oscillographic methods in the examination of photo-cells is limited to ascertaining their inertia and sensitivity under working conditions. The arrangement of Fig. 361 is very useful in determining both of the factors mentioned.[17] By means of a slotted disc and a narrow slit, shown diagrammatically, a pencil of light is directed on to a photo-cell for a short interval of time, and this illumination is made incident suddenly on the cell and suddenly cut off. By using a high-speed motor and plates about $\frac{1}{2}$ metre diameter, a speed of revolution of about 75 m. per sec. at the cut-off can be obtained. If the slotted disc has a width of 0·25 mm., then the rise and fall of the light flux occurs in $\frac{1}{300000}$ sec. The absolute value of the light passing through the slot when strong sources with optical focusing are used is quite large enough to produce ample voltage changes across a relatively small coupling resistance R. The inertia of the photo-cell is shown by the rounding off which becomes visible in the oscillogram of the voltage. Care must, of course, be taken that inertia greater than that of the intermittent light source does not occur either in the photo-cell circuit or in the amplifier. This condition is easily met by suitably choosing the resistance R and designing the amplifier accordingly. The amplitude of the voltages determined from the oscillogram and the degree of amplification is simultaneously a measure of the dynamic sensitivity of the photo-cell under the existing conditions. In view of the high tracing velocities which occur in this case, it is advisable to form stationary figures with the assistance of a synchronized time deflection. If the fluorescent screen is sufficiently free from after-glow, a cathode-ray tube can also be used in the formation of an intermittent light stream (see Chapter IV, page 483), as also the arrangement recommended at the end of Chapter III. But the conditions of illumination are not then so satisfactory, and there is difficulty in reducing the resistance R sufficiently without the photo-electric voltage becoming of the same magnitude as that due to Schrot effect. Kerr cell combinations are sometimes used for the creation of rapid intermittent light pulses. It is usual in such a case to compare the shape of the high or medium frequency modulating the Kerr cell with that at the output of the amplifier for various frequencies.

The cathode-ray tube is used as a measuring instrument in television, in addition to its use for the determination of time lag, principally for modulation control, for testing amplitude filters, for comparing signal voltage with that due to Schrot effect, for phase measurements, and particularly for determining phase changes near the upper and lower frequency limits of the whole equipment. The cathode-ray tube is also used for tracing the dynamic characteristics of neon lamps in mechanical television receivers. A circuit [18] for tracing the

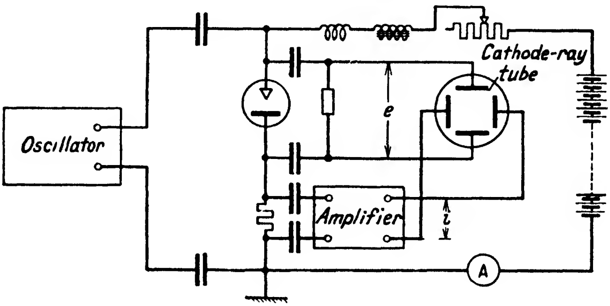


FIG. 362. CIRCUIT FOR TRACING THE CHARACTERISTICS OF A NEON LAMP

current-voltage characteristic of neon lamps is given in Fig. 362. The neon lamp under investigation strikes from the d.c. source shown, and the value of the current passing continuously is then adjusted to a mean value by the regulating resistance.

An alternating current is superimposed on this initial current through an a.c. circuit which is separated from the d.c. circuit by the combination of chokes and condensers shown. The a.c. of the required amplitude is taken from an oscillator supplying frequencies up to 100 000 cyc. The voltage at the neon lamp which is independent of the current if the modulation is correct, is taken to the vertical pair of plates. The current through the neon lamp is taken as a voltage drop across a small resistance of a few ohms and is brought up to the amplitude required for deflection by an amplifier which has a perfect frequency response. In the voltage as well as the current-measuring circuit, the capacitances in circuit ensure that only the a.c. component is measured. In this circuit, the inertia of the neon lamp is shown in the dynamic characteristic by the formation of loops.

2. **Examination of Complete Equipment.** The characteristics which result from a number of single components is the deciding factor in forming judgment on the whole apparatus. Investigations on the resultant characteristics are, in h.f. technique, generally made with transmitters and receivers. Distinction should be made between cases where investigations are made on the equipment as a whole, and those in which measurements are taken at various points of the apparatus in operation.

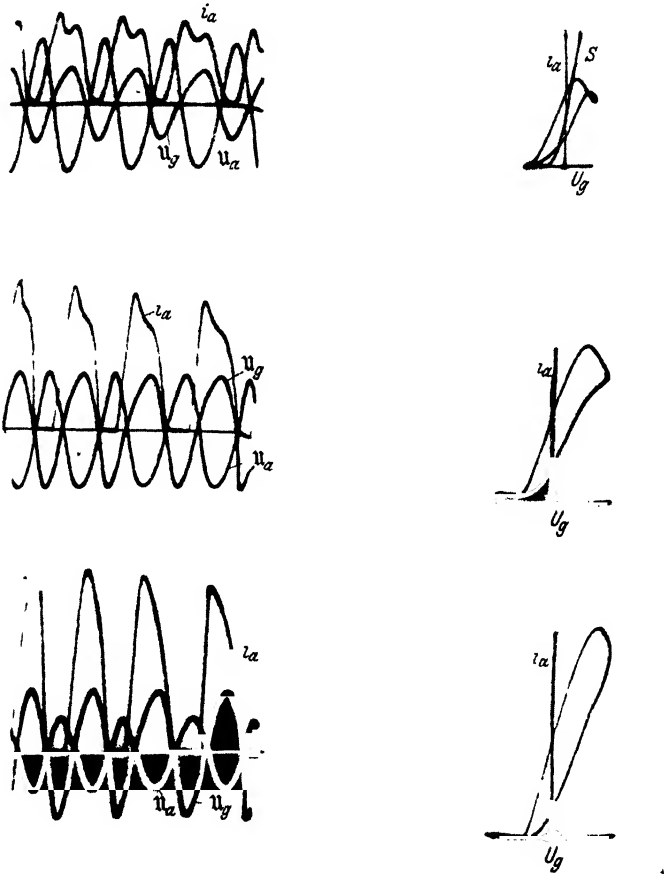


FIG. 363. RELATION BETWEEN VOLTAGE AND CURRENT IN A VALVE OSCILLATOR

(A) EXAMINATION OF TRANSMITTERS. An important use for the cathode-ray tube in the examination of transmitters is the tracing of current and voltage curves. Oscillograms of the configuration of anode current and voltage and alternating grid voltage are of special importance for teaching purposes. Fig. 363 shows several records of a source of low frequency by Kammerloher under three different conditions of operation. In order to carry out similar investigations on high-frequency transmitters, correctly synchronized valve or thyratron discharge tubes are necessary to obtain stationary figures of the

FIG. 364. OSCILLOGRAM OF A MODULATED H.F. OF A BROADCAST TRANSMITTER TAKEN AT THE RECEIVER END

transmitter frequency. With single traverse it is possible to get sufficient brilliancy for the tracing sweep only with medium or high voltage oscillographs. Furthermore, the oscillograph of the rising and fading curves, with sudden switching on and off of the transmitter output, are particularly instructive in the case of telegraphy and television transmitters. From these curves the damping of the transmitter can be determined. A problem which sometimes calls for solution is the determination of the amplitude of various disturbing voltages such as hum from rectifiers.

For the measurement in question the use of the voltage divider discussed (Chapter II, page 211 *et seq.*) may be necessary according to voltage and output conditions, as is also the complete electrical and magnetic screening of the entire measuring equipment, including the cathode-ray tube. For examination of radio transmitters of the highest power available to-day, it has been found sufficient to build the tube into a double or triple armoured metal case. It is usual to place these boxes

inside one another so that a space of several millimetres is formed between them. The suspension of the screening boxes, which are insulated from one another, prevents voltage drop due to eddy current from being communicated electrically to the inner screens.

The cathode-ray tube is almost indispensable in the measurement of the degree of modulation of transmitters. The degree of modulation measured can be read off from the oscillogram of the h.f. oscillation. Fig. 364 shows the oscillogram of the modulated h.f. of a radio transmitter which was taken at the receiver end with a gas-filled tube. The degree of modulation, even when the latter is not periodic, can be controlled accurately by observing the configuration of the curve in a rotating mirror. In order to get an oscillogram free from errors, high-vacuum

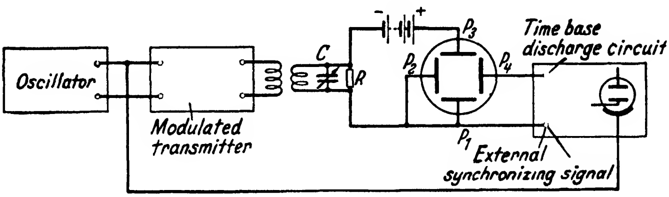


FIG. 365. ARRANGEMENT USING ELECTRICAL TIME DEFLECTION FOR DETERMINING DEGREE OF MODULATION

tubes or gas-filled tubes which are free from origin distortion should, if possible, be used. If, for any reason, such tubes are not available it is of assistance, with the older forms of gas-filled tubes, to apply a bias of 50–100 volts and so displace the origin position of the cathode ray far beyond the point where the normal displacement of the zero point occurs, since the latter area is particularly critical in the h.f. range. The arrangement for electrical time deflection for determining the degree of modulation which, of course, produces stationary figures only from periodic modulations, is illustrated in Fig. 365. This simple arrangement can be highly recommended for visual observation of non-periodic modulation, but in such a case the leads to the synchronizing circuit must be opened. The resistance R in the drawing must be small compared with the internal plate resistance of the tube—and this must receive attention in the case of older types of gas-filled tubes—the battery shown provides the necessary pre-deflection of the ray in order that the highest h.f. amplitudes present shall not come into the zone where origin

distortion occurs. With periodic modulation the arrangement produces stationary figures. The tracing of a figure such as that obtained by Kammerloher with a similar but older arrangement

FIG. 366. OSCILLOGRAM OF A MODULATED H.F. OSCILLATION WITH SYNCHRONIZED ELECTRICAL TIME DEFLECTION

is illustrated in Fig. 366. The degree of modulation is quite simply calculated from the relation

$$K = (a - b)/(a + b) \quad . \quad . \quad . \quad (75)$$

The method, which can be easily understood from Fig. 366, for the determination of the amplitude conditions from the highest to the lowest values, is to be recommended if errors in deflection due to irregularly distributed wall charges, etc., are present.[19]

Another very precise way of measuring if pre-deflection is used is the trapezium method, the principles of which have already been explained in detail above (Chapter III, page 388 *et seq.*). If the determination of the degree of modulation is to be made near the transmitter, the method should be varied so that the modulating low frequency is applied directly to one pair of plates. There appears on

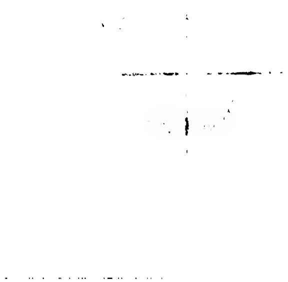


FIG. 367. TRAPEZIUM FOR DETERMINING THE DEGREE OF MODULATION AT THE TRANSMITTER

the fluorescent screen a trapezium from which the highest and lowest voltage can be read and, according to which the degree of modulation can be calculated from the equation just given. The photograph of a trapezium obtained in this way is given in Fig. 367. If the transmitter is 100 per cent or fully modulated, then the edges of the illuminated surface will show the modulation characteristic of the transmitter. In contrast to the rectifier characteristics illustrated above, non-linear performance is shown at high voltages. If phase displacements exist between the modulation curve of the high frequency and low frequency—the latter is easily produced if the trapezium method is used on the receiver side, and phase changes occur in the rectifier and amplifier units —two ellipses will appear on the fluorescent screen. In this case also, as will be seen from the diagram in Fig. 368, the determination of the largest and smallest amplitudes, and consequently the degree of modulation, presents no difficulty.[20]

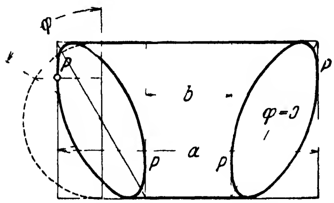


FIG. 368. DETERMINING THE DEGREE OF MODULATION FROM A DISTORTED TRAPEZIUM, PHASE DISPLACEMENT BEING PRESENT

It is of the greatest importance when assessing transmitters to know how powerful is the undesired frequency and phase modulation when the desired amplitude modulation is being carried out. Frequency and phase modulation are particularly objectionable, since they produce considerable distortion with selective fading near the receiver. Among the various processes which are known for measuring them are those which employ oscillographic methods, and also the clear and simple method published by A. Heilmann which deserves special mention.[21] Heilmann's method enables phase changes of the modulated h.f. oscillation occurring during a modulation period to be read off simultaneously with the degree of amplitude modulation. It is based on the comparison of the oscillation to be investigated with an auxiliary oscillation of constant angular frequency. By vector representation of a.c. values, a sinusoidal oscillation corresponds to a vector which rotates at a constant velocity Ω, and describes a circle. A modulated oscillation is shown in the same way except that now, as a consequence of change in magnitude of the vector, its end point no longer follows a circular path

but a spiral shaped curve, and so covers a ringed surface the width of which depends on the degree of modulation k (see Fig. 369). As long as the carrier frequency Ω is constant, equal angles will be traversed in equal periods of time in both cases. If, however, the frequency alters in accordance with any time law, then the angles within this period will be different.

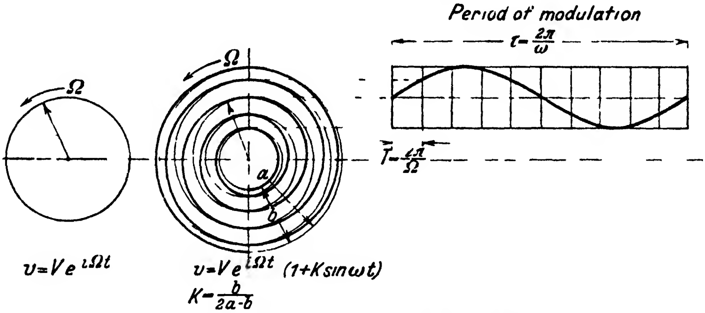
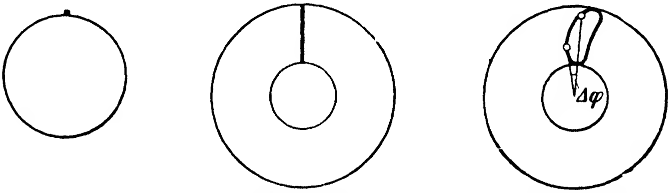


FIG. 369. VECTOR REPRESENTATION OF AN UNMODULATED AND A MODULATED OSCILLATION ($\Omega - 10\omega$)

If a timing mark is introduced in such a way that the vector during certain periods of time is increased, decreased, or modulated in its intensity, short time impulses will appear on the circumference of the circle. If the distance between consecutive impulses is equal to the period of the oscillation under



Unmodulated | *Modulated (without phase modulation)* | *Modulated (with phase modulation)*

FIG. 370. CIRCULAR TIME SCALE OF A SCREEN FIGURE OF A H.F. OSCILLATION UNDER VARIED MODULATION

investigation in its unmodulated condition, then the time mark will always appear in the same position on the circumference of the circle (see Fig. 370 left). If, now, the oscillation is modulated, the time mark will travel to and fro within the circle in the direction of a straight line towards the centre of the circular ring if phase modulation is not present (Fig. 370,

centre). If, however, the transmitter shows frequency or phase modulation, then the time mark will move to and fro sideways according to the extent of the phase change, and will describe in the circle a curve which shows directly the phase change independently of the modulation phase. At the same time, the phase change between two different modulation phases is denoted by the angle contained by the lines joining the centre of the circles to the relative time marks (Fig. 370, right).

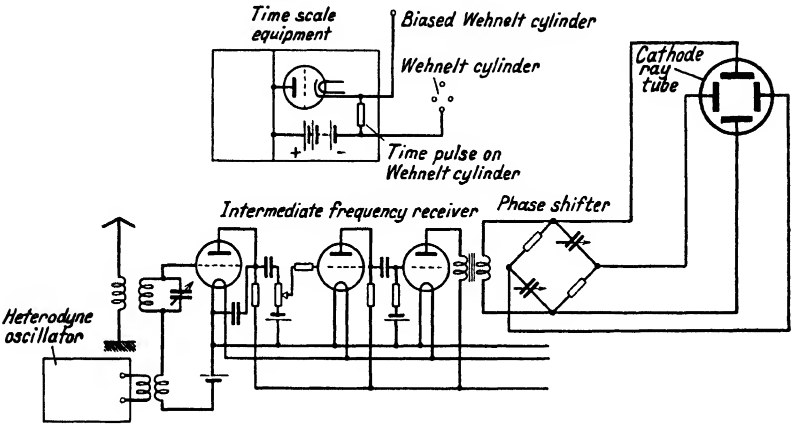


FIG. 371. CIRCUIT FOR STROBOSCOPIC EXAMINATION OF FREQUENCY AND PHASE MODULATION FOR AMPLITUDE MODULATED TRANSMITTERS

The principle of the measurement discussed can be simply carried out by the cathode ray tube in the circuit shown in Fig. 371. The original h.f. oscillation is first converted by the usual superheterodyne method into intermediate frequency oscillations. Tendency to oscillate is in this way avoided. The phase and amplitude changes measured at the intermediate frequency are identical with those of the actual transmitter oscillation. By means of the phase shifting device, two deflecting voltages 90° out of phase are applied to the cathode-ray tube, so that the luminous spot describes circular or spiral figures on the fluorescent screen as shown in Fig. 369. If the modulation frequency is not a simple sub-multiple of the carrier frequency, then an almost regularly illuminated circular surface will be visible on the screen. If, for instance, the application of short voltage impulses to the brightness control electrode gives rise to a time mark, then marks will occur in

the illuminated circle which shows directly the nature of the phase changes. Fig. 372 shows a photograph obtained by Heilmann in which time marks are secured by using short voltage impulses at one of the deflection systems. In order that the time mark may remain stationary, the auxiliary frequency must be brought into exact synchronism with the intermediate frequency. The auxiliary frequency generator must be quite constant. The intermediate frequency must not be too low, because, finally, the phase-shifter will no longer give a phase displacement of 90° for the side bands of the carrier frequency. If the ratio between modulation frequency and intermediate frequency is small, this defect can be ignored.

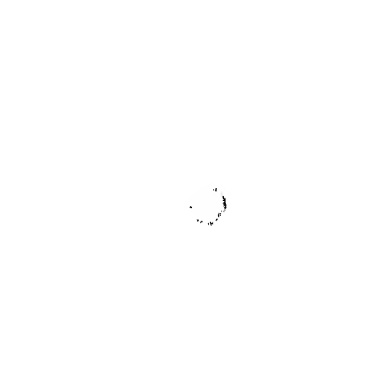


FIG. 372. SPIRAL FIGURE WITH TIME SCALE OBTAINED STROBOSCOPICALLY SHOWING PHASE MODULATION AND TRACED FROM A MODULATED H.F. OSCILLATION

(B) EXAMINATION OF RECEIVERS. In the case of examination of receivers an important use for the cathode-ray tube is the determination of the potential at various parts in the apparatus. The particular problem here is testing the sensitivity, finding the cause of distortions, and evaluating the magnitude of disturbing voltages. Fig. 373 illustrates a circuit for testing

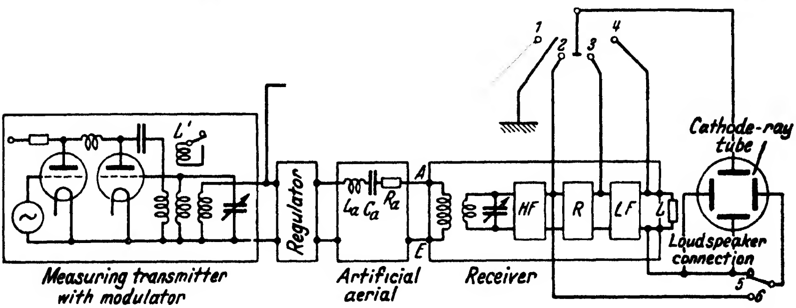


FIG. 373. ARRANGEMENT FOR CARRYING OUT INVESTIGATIONS ON RECEIVERS

receivers in which the cathode-ray tube measures voltage values of varied magnitude. With the switch on contact 1, the mean amplitude, and possibly by simultaneous use of a rotary mirror, the degree of modulation is determined. In position 2, the h.f. voltage at the grid of the rectifier (detector) and in positions 3 and 4 the l.f. voltages in the grid and anode circuit of the last stage are measured. In addition, the detector

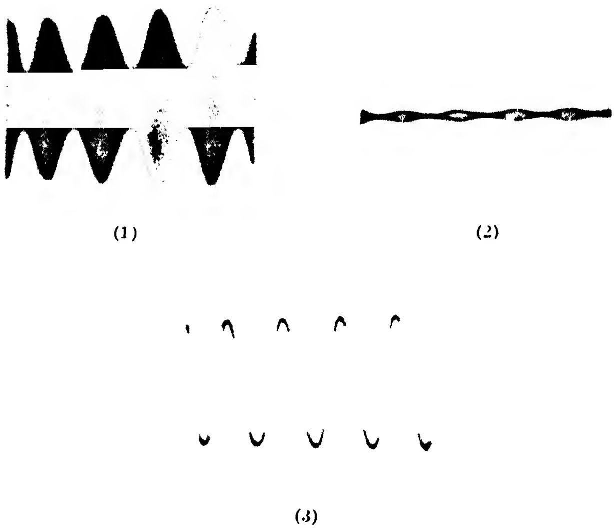


FIG. 374. (1) MODULATED H.F. (2) VOLTAGE PRECEDING THE DETECTOR (3) VOLTAGE SUBSEQUENT TO THE DETECTOR AND MEASURED ACROSS THE ANODE RESISTANCE

characteristic can be traced with the assistance of the second pair of deflector plates if the corresponding switch is on terminal 6 and the selector switch on contact 3. Oscillograms of the voltages corresponding to switch positions 1, 2, and 13 of the testing apparatus are reproduced in Fig. 374, (measurement by Kammerloher).

Most of the data required for appraising receivers (voltage sensitivity, degree of h.f. amplification, operation of the detector, modulation range of the detector characteristic, degree of l.f. amplification, and modulation range of the last stage) can be obtained by means of the testing equipment discussed, in combination with a calibrated test regulator.

Furthermore, when the carrier frequency of the measuring transmitter is altered, the other properties of the receiver (selectivity curves, etc.) can be ascertained. Again, when the modulation frequency changes, the resulting frequency characteristics of the receiver can be determined by measurement.

The investigation of mains noise forms an important question. It is easy by oscillographic means to determine the source of origin of hum and to find the most economic design of the mains components, since the investigation of the percentage fluctuation of d.c. sources occurs also in the case of generators, etc. Let us look more closely at the practical methods used

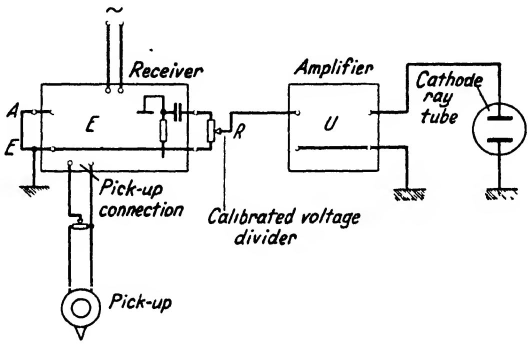


FIG. 375. ARRANGEMENT FOR INVESTIGATING NOISES FROM SUPPLY MAINS

in the examination of mains equipment. Fig. 375 shows a convenient circuit in which the percentage fluctuation is increased in amplitude by a 2- or 3-stage amplifier to be suitable for deflection. The potentiometer provided, whose total resistance must equal that of the loudspeaker, consists preferably of a calibrated voltage divider. The hum factor, which is defined as the ratio of amplitude of the mains noise to the maximum signal amplitude, can be determined by measuring the length of the fluorescent stroke at full loading of the final amplifier and that which exists when the receiver is not loaded. For the determination of the hum factor only a portion of low resistance should be tapped from the voltage divider. It is advisable when tracing the curve of the mains noise to use a much larger voltage in order to trace all the details of the curve.

Let us examine a few noise oscillograms as examples.[22] Fig. 376 shows on the left a typical outline of mains noise if

the anode voltage is supplied by a full-wave rectifier, and grid and heater voltages are supplied from a d.c. source. The right-hand curve corresponds to the mains noise when directly-heated valves from an a.c. supply are used with the usual centre-point tapping for connexion to the grid circuit. In this

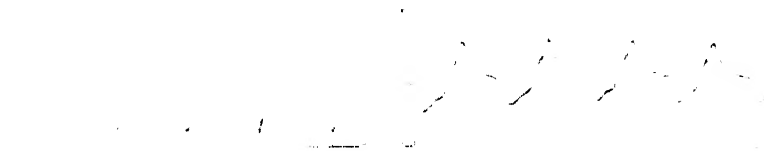


FIG. 376. ANODE DISTURBANCE (*left*) AND HEATER CIRCUIT DISTURBANCE (*right*) IN THE OSCILLOGRAM

oscillogram, grid and anode voltages are taken from batteries. When the heating and anode current circuit disturbances are superimposed a more complicated picture results (Fig. 377).

Instead of tracing the resonance curve point by point and

FIG. 377. DISTURBANCES IN HEATER AND ANODE CIRCUITS SUPERIMPOSED

the audio frequency response curve as specified in the discussion on the testing of receiver circuits, methods employing slow registration are used for more precise recording. Fig. 378 illustrates a circuit for the slow registration of such curves. If resonance curves are to be registered it is necessary that the wavelength of the transmitter should be altered with time in accordance with known laws. If the effect of frequency variation is to be measured, then the wavelength of a second transmitter which interferes with that of the first should be continuously varied. Calibrated condensers of special design are

included in the equipment most conveniently used for varying the frequency, and such are described in Chapter III, page 395 *et seq.* In order that dependence on amplitude may be excluded from the recording, the h.f. voltage produced in the oscillatory

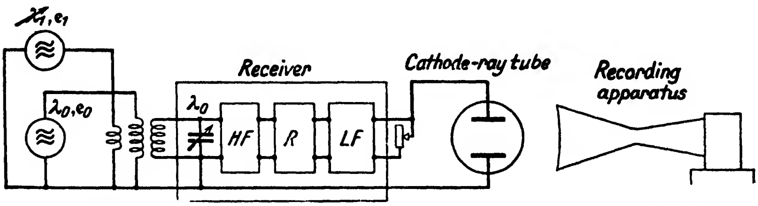


FIG. 378. ARRANGEMENT FOR RECORDING THE OVERALL FREQUENCY CHARACTERISTIC OF A COMPLETE RECEIVER

circuit by the varying frequency should be low compared with the voltage injected into the oscillatory circuit by the constant frequency transmitter. A record obtained with the arrange-

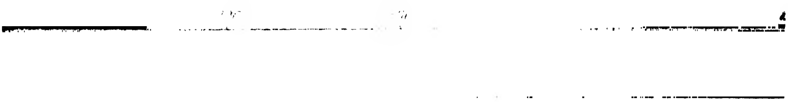


FIG. 379. RECORDED FREQUENCY CURVE OF AN OLD RECEIVER WHICH INCORPORATES GRID CURRENT RECTIFICATION AND WHICH SHOWS A POOR UPPER FREQUENCY RESPONSE DUE TO REDUCED DAMPING IN THE OSCILLATORY CIRCUIT

ment is illustrated in Fig. 379. This represents the resultant frequency curve of a receiver incorporating reaction.

3. **Examination of H.F. Radiations.** In the examination of high frequency radiation the cathode-ray tube is primarily used for measuring field strengths and degree of modulation, as a directional indicator, and as a means of measuring echo signals of short duration.

(A) MEASUREMENTS OF FIELD STRENGTH. The configuration of the field can be directly recorded if the voltage furnished by the output side of an efficient h.f. amplifier is applied to one pair of the plates in a cathode-ray tube, and the length of the fluorescent stroke is recorded with the apparatus described previously (Chapter II, page 328). The advantages enumerated above will be obtained. In addition, with this method there is the extra advantage that the magnitude of the modulation

which existed at various times, can be estimated simultaneously from the record, [23] If modulation is not effected by a periodic oscillation, but by complicated and continually changing oscillations such as always occurs with speech and music, then the points of reversal of the h.f. oscillations vacillate between an upper and a lower limit from which an average degree of modulation can be deduced. In photographic recording the space between the points of reversal of the cathode ray appear more prominent. With an unmodulated h.f. oscillation the points of reversal are always at the same height, a luminous band can be seen in the record, and the limits are particularly well marked. The registration resembles that of a good pick-up

FIG. 380. RECORD OF FADING SHOWING SIMULTANEOUSLY THE APPROXIMATE VARIATION IN DEGREE OF MODULATION

as given previously. If the h.f. is modulated by speech or music, the points of reversal are very irregular. In the tracing a diffuse band, from the width of which the average degree of modulation can be deduced, appears at the edge of the luminous surface.

The facts described can be clearly seen from the record shown in Fig. 380. The height of the curve above the abscissa axis gives the field strength and the width of the band relative to the height indicates the degree of modulation. The complete equipment used for making this record is shown in Fig. 381. On the left is the equipment for measuring the strength of field allowing absolute values of this variable to be recorded; on the right is the receiver with a tuning band of 10^4 cyc. The cathode-ray tube and the recording equipment are in the screened box visible on the right. Complete screening of this part of the circuit is necessary to avoid back-coupling. An interesting variation of this arrangement consists in connecting

various aerials in turn to the input side, particularly frame aerials oriented in various planes. In this way it is possible

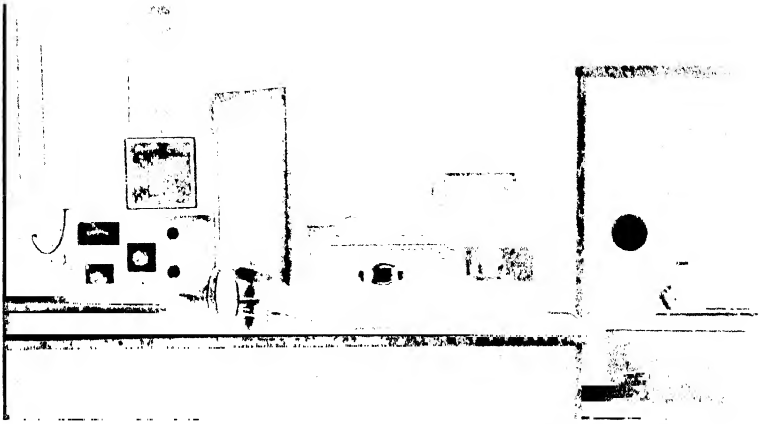


Fig. 381. Arrangement for Recording Field Intensity

to record simultaneously fluctuations which take place in various components. Fig. 382 shows a record in which two frame aerials at right angles to one another were connected up

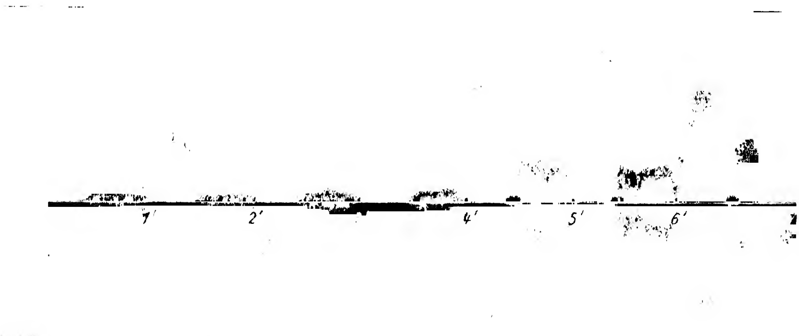


Fig. 382. Simultaneous Recording of the Field Strength of Two Frame Antennae at Right Angles to One Another and taken with an Old Type Gas-filled Tube

in time intervals of about ½ min. Naturally in this case much more rapid switching over is possible, so that the outlines obtained intersect one another. All the fine details of the outline can be recognized. High accuracy of measurement

can only be expected when a high-vacuum tube is employed, particularly in the case of this type of recording.

(B) THE CATHODE-RAY TUBE AS A DIRECTIONAL INDICATOR. In relatively simple circuits the cathode-ray tube is capable of giving an indication of the direction of incoming signals. A diagram of an arrangement for giving directional indication with two perpendicular frame aerials and using the cathode-ray tube is shown in Fig. 383. This arrangement was published by Watson Watt and used by him to determine the exact location of distant storms.[24] Two frame aerials of exactly the same construction separate the incoming signals into N.–S. and E.–W. components, the resultant voltages being amplified equally by

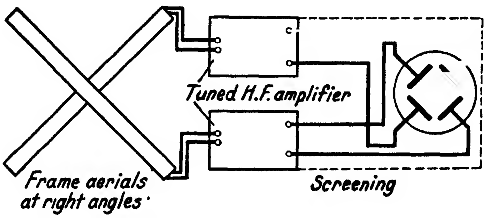


FIG. 383. ARRANGEMENT FOR DIRECTIONAL INDICATION WITH THE CATHODE-RAY TUBE

amplifiers which are exactly alike and applied to each pair of plates of the cathode-ray tube. The resultant becomes directly visible on the screen, and, if orientation is correct, represents the direction of incidence. In order that a fluorescent stroke may appear on the screen, it is necessary for both components to be in phase. This can be achieved by tuning the symmetrical amplifiers to the same wavelength. Matching for symmetry in the measuring device can be simply carried out, for instance, by an auxiliary transmitter arrangement, impulsed by time discharges, and being set up some distance from the cross-frames so that the same e.m.f. is induced in both. In the shorter wave-band it is difficult to attain the desired results by this method. Equality of phase of both components is not possible in practice if radiation reaches the receiver by an indirect as well as a direct path. Other methods for directional indication have, therefore, been developed for short waves. A very neat method of measuring employed by Friiss[25] for the determination of azimuth and elevation angles of the incident short waves is based on the fact that the waves

are heterodyned by a local oscillator. With two receivers set up a certain distance apart, and connected to each pair of plates of the cathode-ray tube, the phase of the resultant interference note which depends on the direction of incidence, can be compared in the two receivers. The varied orientation of the receivers as well as the relation between the fluorescent figure and the direction of incidence, can be seen from the diagrams of Figs. 384 and 385. Here, again, it is important that symmetry

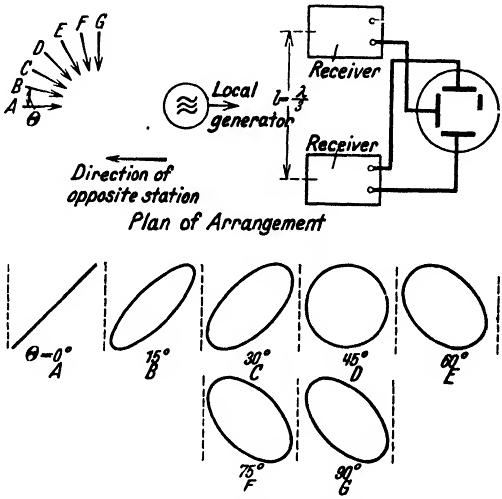


FIG. 384. ARRANGEMENT FOR DETERMINING THE AZIMUTH ANGLE OF INCOMING WAVES

is assured, i.e. the receivers are of equal sensitivity. Furthermore, the local oscillator must be of very constant frequency.

(c) DETERMINATION OF THE HEIGHT OF THE HEAVISIDE LAYER. When signals are sent out by wireless telegraphy, echo phenomena can occasionally be noticed in the receiver and this may lead to observation errors in the interpretation of the succession of transmitted signals. Besides the main signal which arrives at the receiver after a period of time corresponding to the distance and the velocity of propagation of electromagnetic waves, a further signal or signals is recorded some time after the primary one. If these echo signals are observed at a relatively short distance from the transmitter, and if they follow the main signal quickly, then the electromagnetic waves

have been reflected from the so-called Heaviside layer. This is accepted as a layer spread out at a height of about 100 km. above the earth's surface and having a large number of free electrons. On account of its relatively good conductivity, it reflects part of the waves from the earth. The investigation of these so-called *short duration echo phenomena* is important both by reason of its effect on receiver operation, and the valuable information it provides about the physical nature of

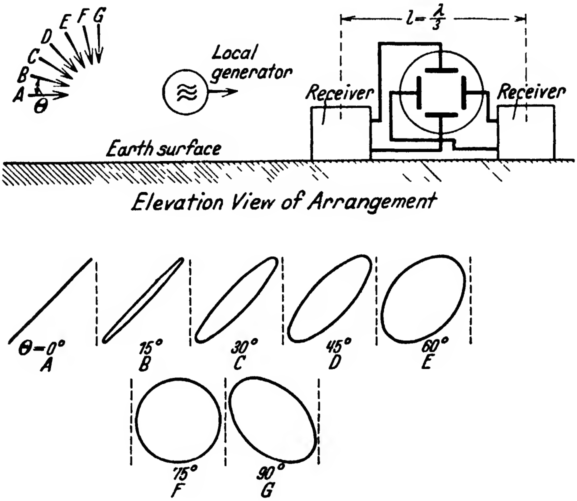


FIG. 385. ARRANGEMENT FOR DETERMINING THE ANGLE OF ELEVATION OF INCOMING WAVES

the Heaviside layer. The first oscillographic determinations were carried out by E. V. Appleton,[26] M. A. F. Garnett,[27] and American authors.

A further process for measuring the height was published by Breit and Tuve[28]. Short groups of waves are sent out from the transmitter; the incoming short signals are recorded in the receiver; several signals in the receiver then correspond to a single wave group of the transmitter. The time period between the echo and the direct signal is observed. From the known distance between transmitter and receiver and the approximately correct assumption that the velocity of the earth waves is the same as the velocity of light in non-ionized air, the time taken by the direct signal can be calculated. If

the difference in time observed between the main signal and the echo signal is added thereto, the time taken by the echo signal is obtained. A knowledge of the time taken by the echo signal makes possible the determination of the height of the Heaviside layer. By this method, the relation between the effective height and the distance between transmitter and receiver, the time of day and year, etc., can be found. The

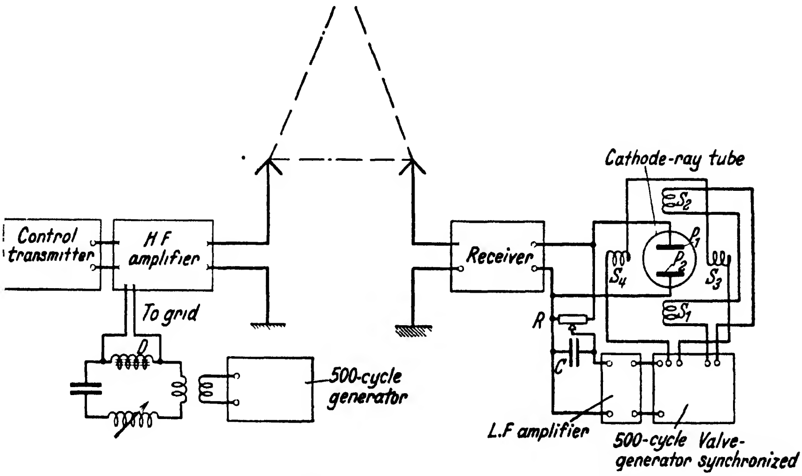


FIG. 386 CIRCUIT FOR MEASURING THE HEIGHT OF THE HEAVISIDE LAYER (GOUBAU AND ZENNECK)

recording of main signal and echo is best effected by means of the cathode-ray tube[29]; the cathode ray traverses the oscillogram surface at known velocity, and is synchronized with the signals from the transmitter. The curve is modulated by the incoming signals, and the peaks in the trace show the difference in time of arrival. In particular, two tracing processes are in common use. Either the time traverse of the fluorescent spot takes place in a polar curve, or the time deflection is actuated by discharge pulses. Fig. 386 illustrates the first process in the arrangement of Goubau and Zenneck.[30]

The short impulses which serve to modulate the valve transmitter are produced by a saturated iron choke. It is included in a condenser circuit which is fed by a 500-cyc. generator. If the applied voltage is sinusoidal, a voltage is obtained at the terminal of the choke, and this has an impulse-like

wave-form with respect to time. The actual transmitter consists of a control transmitter and an h.f. amplifier. The grids of the h.f. amplifier valves of the last stage are so highly biased negatively that in the quiescent state no anode current, and therefore no aerial current, flows. The iron choke is connected in the grid circuit of this stage. Short-wave groups of about 10^{-4} sec. duration are received 500 times per sec., and their outline is traced with the cathode-ray tube as shown in Fig. 387. The voltage taken direct from the aerial is conducted to the tube plates for vertical deflection of the cathode-ray beam. The horizontal deflection is effected by the current of a condenser circuit which is fed by a 500-cyc. generator.

FIG. 387. TIME VARIATION OF THE WAVE GROUP OF A SIGNAL

The receiving equipment performs two functions. First, it has to receive and trace the signals. In the circuit of Fig. 386 this is done by vertical electrical deflection of the cathode-ray beam. The deflection plates P_1P_2 of the tube are directly connected to the receiver. Each signal from the transmitter produces on the condenser formed by P_1 and P_2 a charge which deflects the fluorescent spot vertically during the persistence of the signal. Of course, radial deflection of the spot can also be secured by adding a second pair of deflection plates or, better still, control can be made at the brightness-control electrode, thereby making evaluation easier and more accurate. The second function of the receiving apparatus is the production of a linear time deflection which is exactly in synchronism with the 500 period generator of the transmitter. In the circuit shown, the time deflection is carried out by means of a rotating magnetic field acting on the cathode-ray tube. The rotating field is produced by a 500 cyc. valve oscillator to which the deflecting coils S_1, S_2, S_3, and S_4 are connected. Synchronization of the valve oscillator is effected by signals taken up by the receiver being induced on the grid circuit of the valve oscillator through a voltage divider R and an l.f. amplifier. The conditions of operation of the valve oscillator and the amplitude of the control voltage, are so adjusted that the valve generator

is locked by these signals. A simpler method of synchronization used in practice consists in transmitting the synchronizing signal through a telephone cable or over a long-wave channel. This kind of synchronization eliminates the following difficulty. If short waves are used over any distance, an actual signal is not received on account of the absorption of the earth waves. There is no definite synchronizing impulse and zero point for the determination of the traversing time. For instance, the position of the direct signal can be marked on the screen of the tube by a long wave whose earth wave is sufficiently strong at the point of reception. The shape of the stationary image obtained when the direct signal only is received is shown in Fig. 388. If, in

FIG. 388. PHOTOGRAPH WITHOUT ECHO

FIG. 389. PHOTOGRAPH WITH ECHO

addition to the direct signal D, an echo is also received, the outline becomes that shown in Fig. 389. The effective height from which an echo is received is shown in the photograph by the angular distance of this echo from the main signal. When making records of long duration it is advisable to determine the time taken in photographing a single echo by photographing at the same time the face of a stop watch or by using some other method of time marking.

In Hollmann and Kreielsheimer's[31] method, the time traverse is brought about by a saw-tooth oscillation synchronized with the transmitter signal (Fig. 390). A transmitter radiates every $\frac{1}{50}$ sec. a short signal synchronous with the lighting mains. The release of the signal takes place through a contact K_1 driven by a synchronous motor. The radiated signals reach the receiver and deflect the cathode ray in the ordinate direction through the pair of plates P_1, P_2 of the cathode-ray tube. Time deflection is effected by charging the condenser C from a battery through a saturated current valve. The time deflection must also be repeated 50 times per sec. To do this, the

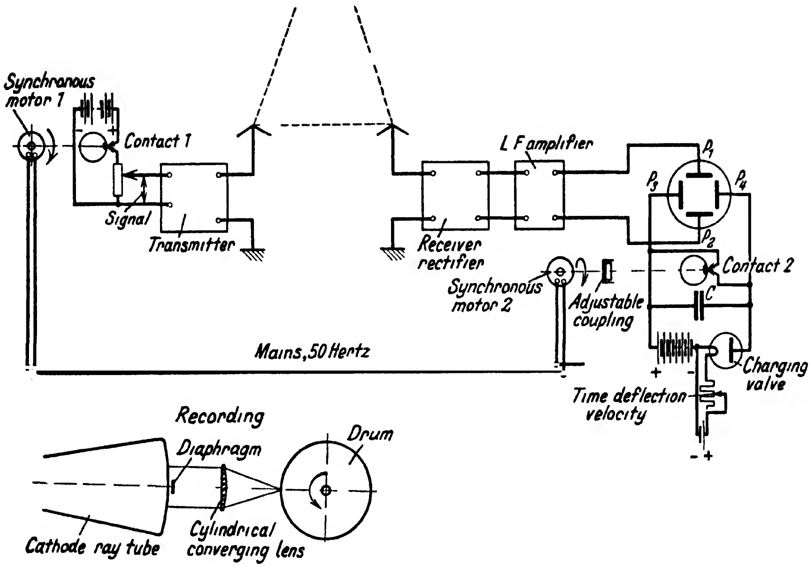


FIG 390 SIMPLE CIRCUIT FOR DETERMINING THE HEIGHT OF THE HEAVISIDE LAYER (*Hollmann and Kreielsheimer*)

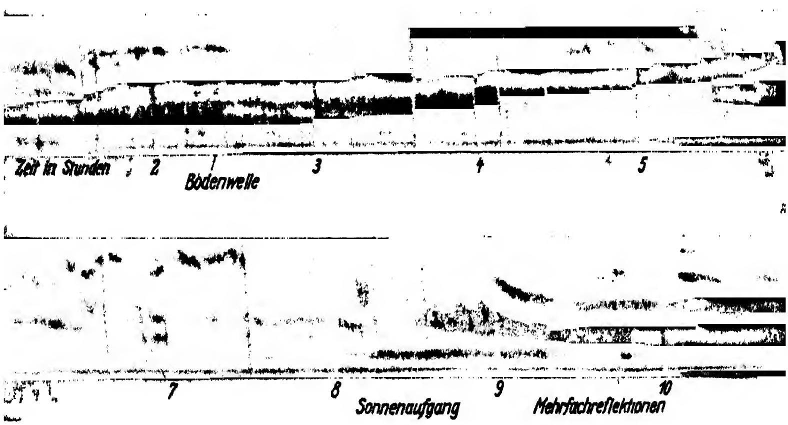


FIG. 391 EXTENDED RECORD OF SHORT WAVE ECHO PHENOMENA (*Hollmann and Kreielsheimer*)

Zeit in Stunden = time in hours Bodenwelle — ground wave
Sonnenaufgang = sunrise, Mehrfach reflektionen - multiple reflections

condenser is discharged periodically through a corresponding contact K_2 synchronously driven from the same mains. For correction of phase displacement, i.e. to ensure that the directly transmitted signal starts at the beginning of the time sweep, the contact K_2 is adjustable in position on the motor axis. The velocity of deflection is variable according to the magnitude of the condenser and the emission of the valve. In order that the complete direct signal may be photographed, the contact K_2 which determines the start of the time deflection, must travel slightly in advance of contact K_1. Fig. 391 shows a continuous record of 10 hours obtained with this apparatus. The record shows very distinctly many multiple reflections, and a particularly beautiful effect at sunrise. For the purpose of recording, the ordinate deflection is focused through a cylindrical lens which causes the time axis to be blocked out (see Fig. 390). In a photographic record, the direct and echo signals are then traced as dots or dashes, the time separation of which denotes the height of the Heaviside layer. By inclining the abscissae about 30°, the authors are also able to include the amplitudes of the various echoes in the record.

III. The Use of the Cathode-ray Tube in Telegraphy and Telephony

The cathode-ray tube is frequently employed in telegraphy and telephony for tracing phenomena of short duration. The problems which occur are in many cases identical with those of h.f. technique; therefore they will be only briefly mentioned where the two cases are the same. In this connexion mention must be made of capacitance measurements, inductances, amplifiers, valves, oscillators, telephones, the investigation of all h.f. and l.f. components used in telephony and telegraphy, as well as the investigation of filter networks frequently used in these applications. The investigation of the formation of transients, particularly in long conductors, is also of importance as, for example, in finding suitable conditions for high-speed telephony and telegraphy. For examining and testing conductors, methods analogous to those used in the measurement of switching-on processes in amplifiers, discussed above, are employed (Chapter III, page 380 *et seq.*). The characteristics of transients, resonance, and damping can be oscillographed in the usual way.

The dielectric losses of a cable can be ascertained by the method noted in Chapter III, page 362 *et seq.* ("Examination of Condensers"). Of particular importance is the oscillographic determination of the source of faults in long conductors. If an overhead line open-circuited at each end, or a cable, is suddenly connected to a source of potential, a wave is produced by voltage rise and is reflected at the free end. If the wave meets a short or earthed circuit in its progress, reflection will also occur at this point, but with voltage drop according to the value of the initial resistance. As this wave in uniform conductors, such as are to be found in practical use, continues to move at constant velocity, the time taken to reach its point

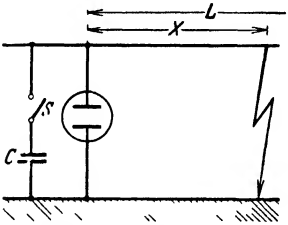


FIG. 392. FUNDAMENTAL CIRCUIT FOR LOCATING A FAULT

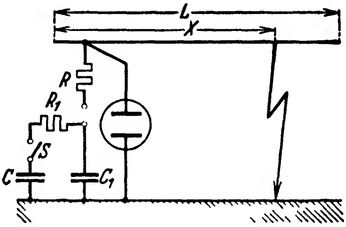


FIG. 393. WORKING ARRANGEMENT FOR LOCATING A FAULT

of reflection, and from this the distance between the origin of measurement and the fault, can be ascertained from the oscillogram of the wave(32). Fig. 392 shows a circuit used for determining the position of a fault. By means of a switch S the voltage V of a condenser C is applied to the conductor L, and the time deflection simultaneously set in motion. As the oscillograph is some distance from this point along the conductor, the deflection plates will only be raised to a voltage v when the wave reaches this point. The distance between the oscillograph and the end of the conductor, under the most favourable conditions should be at least 2–3 per cent of the length of the conductor, otherwise the voltage rise or drop in the oscillogram which indicates the reflected wave would become too small or disappear altogether. According to Fig. 393, this distance can be replaced by the resistance R (which is approximately equal to the resistance of the conductor to the wave) connected at the end of the conductor between the source of voltage and the point of connexion of the oscillograph. In order to show the initial voltage rise on the

oscillogram, the source of current is first switched on to a distortion circuit through the switch S, a condenser C_1, having a time constant C_1R_1, being charged through the resistance R_1. After charging, a spark gap is discharged and through this the wave enters the conductor. Of course, an electron tube circuit can take the place of the spark gap which is particularly suitable for medium or h.f. oscillographs.

Time lags and the time of switching of all kinds of relays used in telephony and telegraphy are frequently found by similar methods of measuring time with the cathode-ray tube.

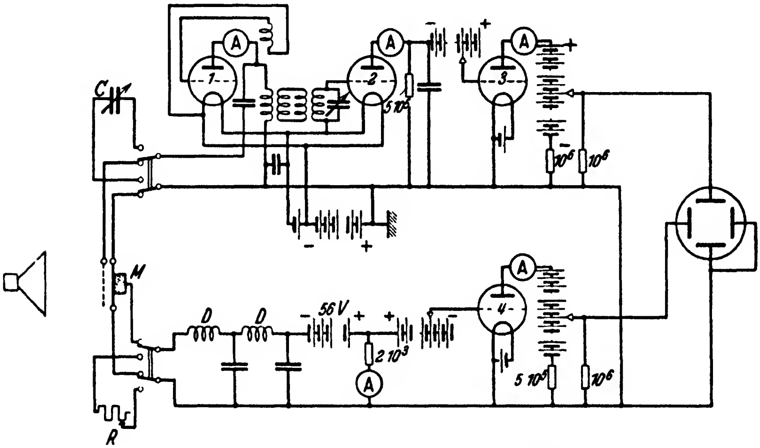


FIG. 394. CIRCUIT FOR EXAMINING A CARBON MICROPHONE

A special application by A. Salinger[33] of the cathode-ray tube in telephone technique will be discussed in detail. Fig. 394 shows a measuring circuit for examination of microphones. The oscillograms obtained are characteristics whose ordinates represent the movement of the membrane and abscissae the resistance of the microphone. As the sensitivity of the cathode-ray tube is not sufficient, amplifiers are provided. In order to observe the constant displacement of the operating point in the microphone at the same time, direct-coupled amplifiers are used in the circuit illustrated. At a short distance in front of the membrane of the microphone M a small perforated counter-electrode is fixed. This counter-electrode with the membrane forms a condenser from the capacitance variation of which the movement of the carbon membrane

is measured. The microphone capacitance is included in the oscillatory circuit of valve 1 (32) so that the frequency of oscillation depends on its capacitance. Just as in the arrangement (Chapter II, page 227 *et seq.*) already discussed above, at the grid of valve 2 and finally across the anode resistance of valve 3, voltages proportional to those across the microphone condenser are produced. The current circuit of the carbon microphone is fed from a battery (56 volts) through a series resistance of 2 000 ohms. The choke network D serves to restrain the h.f. oscillations. The voltage across the resistance is applied to the horizontal pair of plates of the cathode-ray tube after amplification by the resistance-coupled valve 4. Two switches provide a means of calibrating the instrument. By means of one of them the microphone capacitance can be replaced by a variable condenser having a fine adjustment, the capacitance being equal to that measured if the operation of the switch leaves everything else unaltered. With the assistance of the fine adjustment, calibration dots can be fixed on the capacitance axis of the oscillation image. In the same way, the second switch provides for the substitution of the carbon side of the microphone by a resistance W, by the aid of which calibration dots are fixed on the resistance axis of the oscillation image. As a consequence of the inconstancy of the resistance in the carbon housing, and the difficulty of keeping the voltage of all the batteries sufficiently constant, the image wanders to and fro over the luminous screen. The oscillogram given in Fig. 395 was obtained by retracing on transparent paper. In this oscillogram the condition of the microphone is indicated by the dot 1 before the sound vibrations commence; curve 2 shows the image under the influence of a note of frequency 1 170 cyc. The calibration dots were then marked on both axes after which the image of loop 3 and later that of loop 4 were observed. The exciting sound was then switched off. The resistance and the position of the membrane were then indicated

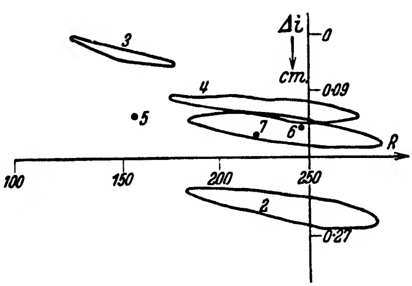


FIG. 395. AN OSCILLATION OF A TELEPHONE MICROPHONE CAPSULE

by dot 5 which, however, slowly wandered towards 6. Switching on the sound for the second time gave curve 7. It can be seen from the oscillogram that the microphone characteristic describes a hysteresis loop.

IV. Uses in Heavy Current Engineering

In heavy current technique the cathode-ray tube is used not only on account of its high speed of recording processes of short duration, but also on account of various other properties which give it, in certain cases, a superiority over the expensive loop oscillograph. One of these advantages lies in the possibility of oscillographing currents and voltages, and tracing their characteristics directly. For current sensitivity, the low voltage cathode-ray tube with magnetic deflection is equal, if not superior, to the loop oscillograph in the region of 10 000 cyc. A deflection of 40 mm. for the loop oscillograph requires a current of 100 mA. for a loop with a natural frequency of 12 000 cyc; this corresponds to a current sensitivity of 0·4 mm. per mA. At the same frequency, the current sensitivity of a cathode-ray tube amounts to about 1 mm. per mA. In making direct voltage measurements there is the advantage that a very small load is involved. Finally, its ability to withstand overloading in making measurements must be mentioned as a fundamental advantage which is particularly important in high current work. Also, its lack of sensitivity to mechanical vibration and the ease with which it can be transported contribute in many instances to the substitution of the cathode-ray oscillograph for the loop oscillograph. The cathode-ray tube also shows its superiority for demonstration equipment as the luminous oscillogram appearing on the brightly-illuminated screen can be satisfactorily observed even in large rooms, particularly when television tubes or projection equipment is used. Almost all the principles of heavy current technique can be clearly demonstrated with the cathode-ray tube, viz. the electric and magnetic field, the magnitude and configuration of the voltage, the important principles involved in phase displacement, the power factor, and the frequency. Fig. 396, which shows an oscillogram of the formation of a rotary field, is an example of an experimental demonstration. Three magnetic coils 120° apart, to which the respective phases of the rotary field are taken, are employed for deflection. The straight

lines of the oscillogram represent the deflections of the coils connected singly, the ellipses each represent deflections by two coils, and the circle the deflection by the rotating field due to all three coils. The determination of mains disturbance in d.c. mains or generators (Chapter III, page 418 *et seq.*) is an important problem. The cathode-ray tube is suitable for such investigations, particularly when harmonics of a high order are present or when voltage peaks are encountered. Furthermore, the tracing of the switching on or off of mains-operated circuits is important. The normal as well as the abnormal phenomena occurring in such cases, and their effects on stations and apparatus, are investigated. The oscillography of short-circuits and transients which are of short duration, the determination of time of operation of oil switches, especially of quick break switches, the measurement of the time elapsing between the excitation of the switch and the establishment of the circuit in the case of various circuits, and circuit relays used in heavy current engineering, may be mentioned amongst the most frequently occurring problems.

FIG. 396. FLUORESCENT SCREEN FIGURE DEMONSTRATING THE FORMATION OF A ROTATING FIELD (MEASUREMENT BY H. MOLLER, HAMBURG)

Fischer and Pungs[34] have undertaken the oscillographic examination of the use of electron tubes as switches.

In the operation of oil switches the pressure which occurs in the switch chamber during the process of switching as well as the switching-off time is of importance. A piezo crystal is generally used as a coupling device (Chapter II, page 229 *et seq.*). When examining the phenomena taking place during the extinction of the arc in heavy-current switches, the variations of the steep and high changes in pressure are of most interest. The pressure which is due to the formation of particles of vaporized oil when the arc is produced by opening the circuit attains a value up to 30 kg. per cm.^{2} and occurs in about 0·01 sec. In high pressure gas switches as well, measurements

are made with a quartz crystal. Re-ignition during reversed voltage is prevented by the cooling effect of the gas flowing through the contacts, which removes ions required for the formation of an arc. Among the special examinations which can be made are the variation of the gas pressure in front of the switch case, the rise in pressure due to heat from the arc inside the case, and also the conditions of pressure existing in the silencing chamber through which the exhaust gases must pass so that the noise of breaking the circuit may be reduced.

Also of interest in switchgear, as well as in high output machines, is the impulse effect which takes place under conditions of short circuit. When examining high current switchgear great care must always be taken to ensure that strong magnetic fields produced by the switching operation do not give rise to disturbances. The extremely rapid initial oscillations which occur in commutating circuits of d.c. and a.c. machines are also of such duration that in most cases they can only be faithfully recorded by means of the cathode-ray tube.

The examination of high-voltage phenomena is a sphere almost exclusive to the cathode-ray tube. In the case of the most rapid changes of this kind only the high voltage oscillograph is suitable for recording. Numerous investigations can, however, be carried out as well with the low or medium voltage cathode-ray tube. The examination of the wave form of the current and voltage is made in the same way as with low voltage circuits, except that the oscillograph tube is connected through a voltage divider to the circuit under examination. Special reference must be made here to a work by Vieweg and Pfestorf concerning which a detailed report has already been given (Chapter II, page 206 *et seq.*). Reference should be made to Chapter III, page 431, concerning the determination of the location of a fault in a short-circuited long conductor. An example of the oscillographic investigation of high voltage equipment is the surge test of transformers. The test unit is subjected to an excitation which is increased till the high voltage winding reaches 110 per cent of its nominal rated voltage, at which point a discharge passes across a spark gap which has been adjusted accordingly. As the testing time amounts to 10 sec. and about four arcs per phase occur during each period, each winding of the transformer is subjected to a total of about 2 000 surges. The distribution of the voltage

rise of such waves in each coil winding is very involved, both spatially and in time, since the coil is a combination of capacitance and inductance. The relation can only be made clear by oscillographic recording.

V. Applications in Acoustics

The examination of equipment used with the cathode-ray tube in electro-acoustics has already been described in detail (Chapter II, pages 226 and 232; Chapter III, pages 395 and 431. Below, a few further uses for the recording of pure acoustic phenomena are discussed.

The phase of sound waves can be determined by the Hollmann

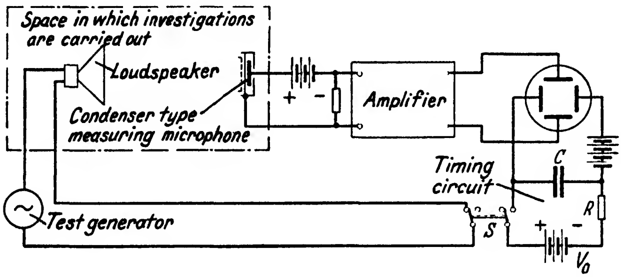


Fig. 397. A Cathode-ray Tube Circuit for Measuring the Duration of an Echo

and Saraga process which has been described already in detail in Chapter I, page 86 *et seq.*

Of great importance is the determination of the sound and echo periods of a room. The circuit of Fig. 397 was used by the author[35] for measuring the acoustic properties of a room at various frequencies. A loudspeaker is excited by an audio-frequency generator producing signals of periodically fluctuating frequency. In the room in which the experiment is carried out there is a condenser microphone as well as a loudspeaker. The output voltage of the microphone amplifier which indicates the intensity of the sound where the experiment is being carried out, is applied to the vertical plates of the cathode-ray tube. At the same instant the frequency generator is switched off, the time circuit, the time constant of which is set by the condenser C and resistance R, is excited by a double-pole change-over switch at the horizontal plates.

Fig. 398 illustrates an echo oscillogram obtained with this

arrangement of circuit. If the time constant of the room is the same as that of the condenser circuit, then a triangular envelope of the oscillogram is obtained, but in other cases the envelope is parabolic. Hollmann and Kreielsheimer used a circuit for determining the height of the Heaviside layer to find the echo times by substituting a loudspeaker and microphone for the transmitter and receiver (Chapter III, page 425 *et seq.*).

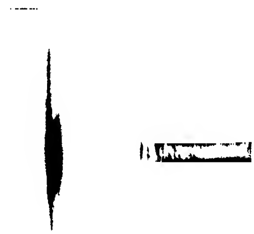


FIG. 398. ACOUSTIC ECHO CURVE

A very neat method for determining the sound and echo times by so-called *acoustic saw-tooth oscillations*, has been published by Hollmann and Schultes.[36] The principle of this arrangement is based on the condenser as a source of electrical energy being replaced by a room as a source of acoustic energy, with an electrical time discharge circuit such as the well-known one using a flashing neon lamp, the transformation of acoustic energy into electrical control potentials, and vice versa, taking place through the microphone and

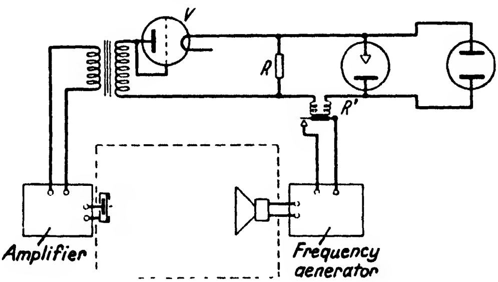


FIG. 399. DIAGRAM SHOWING THE ESSENTIALS FOR PRODUCING ACOUSTIC TIME DISCHARGES ACROSS A SPACE

loudspeaker. It is better to replace the neon lamp by the Kallirotron time discharge circuit which has the advantage that its discharges can be adjusted as desired, and that no appreciable load is required for the control. The fundamental circuit of Fig. 399 with the neon lamp as a control unit operates thus. In the room in which measurements take place there is a loudspeaker as the source of sound fed from a frequency generator as well as a receiving microphone. The

alternating voltages after passing through the amplifier are rectified by the valve V and appear across the resistance R. Connected to this resistance is a neon lamp, the striking current of which switches off the loudspeaker by means of the relay R' when the rectified microphone voltage reaches the striking value. From this instant onwards the sound in the measuring room reverberates until the d.c. voltage from the microphone falls to the extinction value of the neon lamp, and the loudspeaker is again switched into circuit by the relay. Then the sound period starts afresh until the striking voltage

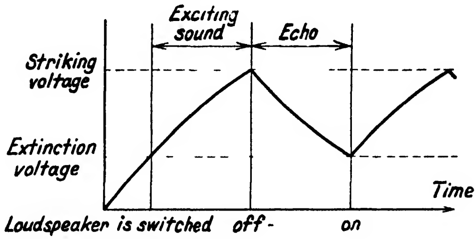


FIG. 400. TIME DISCHARGE CIRCUIT RELATIVE TO THE MICROPHONE VOLTAGE

is reached, and is again followed by the reverberation period, and so on. It can be seen that this causes a fluctuation of the microphone voltage between the two critical potentials of the neon lamp as shown in the diagram of Fig. 400, which shows the outline of the microphone voltage. Fig. 401 shows a spatial-acoustic oscillogram obtained with this time-discharge circuit.

A problem which recurs frequently is the determination of the natural frequency and damping of vibrating acoustic systems, e.g. hollow or empty spaces. A simple solution of the problem consists in exciting the hollow space to acoustic vibration, by means of a condenser spark discharge, for example, and by means of a sound receiver with connected oscillograph equipment recording the reverberations on an oscillogram. The outline obtained shows directly the natural frequency and damping. As an example of a similar use, within the scope of this chapter, reference to oscillography of resonance curves, particularly the measurement of speech and musical vibrations, must not be forgotten. The accessories required for undistorted tracing have already been discussed above (Chapter II, pages 232 and 194).

Sound spectroscopy for the purpose of noise analysis represents a further use for the cathode-ray tube in acoustics. Formerly noise analysis was carried out by the so-called *acoustic exploration method*, the disadvantage of which was that the tracing took a certain time so that it was not possible to observe the spectrum immediately the sound was produced. This was due to the excitation time of the filter used. This time lag occurred not only once but each time the exploring note changed, on account of the band-pass width of the filter. Meyer and Thienhaus [49] have published a new method which uses optical principles for obtaining the spectrogram, and its main advantage lies in the fact that it overcomes the

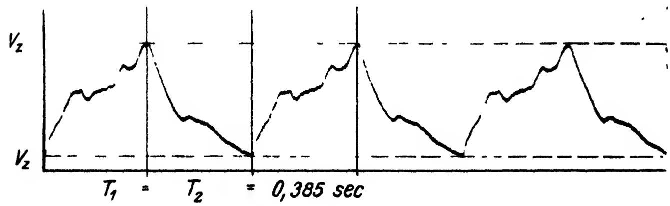


FIG. 401. RECORD OF ACOUSTIC SAW-TOOTH OSCILLATIONS

difficulties mentioned above. If, for instance, a diffraction grating is used, the various paths of interfering rays will correspond to the appropriate wavelengths. This system represents nothing more than an infinite number of tuned resonators each of which emits a note when the sound impinges on it. Here is the possibility of building up the spectrum almost immediately, and with the help of suitable apparatus of making it directly visible. The general arrangement according to this method is given in Fig. 402. It is not possible, of course, to use the sound directly on account of its long wavelength. In order to do so, a frequency transformation must take place, i.e. the acoustic vibrations are superimposed on a carrier frequency which is outside the audible range. The position of the carrier frequency depends on the extent of the sound to be analysed, the desired grating dispersion, and the nature of the sound radiator and receiver over this range. In the case to which reference is made, the frequency of 45 kc. was selected.

The sound, which is picked up in the usual way by a microphone and amplifier, is taken together with the carrier frequency to a push-pull modulator which suppresses the carrier frequency

and produces both the side-bands 40–45 kc. and 45–50 kc. The lower side-band is cut off by a condenser network, so that the next power amplifier receives only the 45–50 kc. band exclusive of the carrier frequency. The frequencies are radiated by a narrow band radiator, and fall on the grating which splits them up as interference images along a focal line. Here they are picked up by a condenser microphone and passed through an amplifier and rectifier. The circular grating used employs steel needles of 3·4 mm. diameter, and they are placed on two sheet-iron plates parallel with one another and separated by

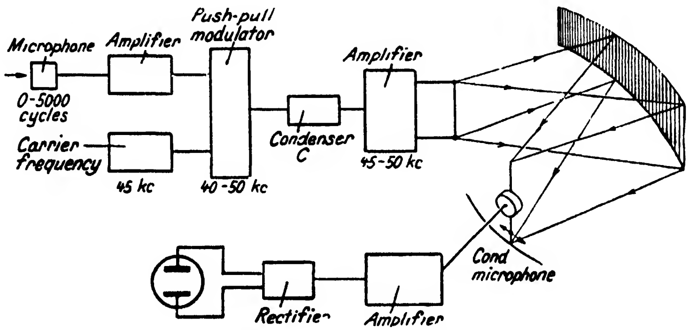


FIG. 402. EQUIPMENT FOR SOUND GRATING SPECTROSCOPY BY MEYER AND THIENHAUS

12 cm. The condenser microphone is pivoted, which permits it to explore the focal line. The pivot is at the same time coupled mechanically with a side deflection of the light ray from the galvanometer which was first used as an indicating device on the output side of the measuring amplifier and rectifier.

If, therefore, the microphone is pushed along the focal circle, the light spot of the galvanometer will describe the envelope of the noise spectrum on the screen or the photographic recording paper. With a sufficiently small natural period of vibration in the galvanometer, the spectrum can be so quickly explored by the rapid movement of the microphone that an image appears which is visually almost stationary. As distinct from this relatively primitive method, Meyer and Thienhaus publish as an improvement the use of the cathode-ray tube with sufficient amplification in place of the rectifier, the spectrum appearing on the luminous screen. The abscissa deflection is produced in a relatively simple way by a direct

voltage across a variable resistance, the magnitude of which varies with the position of the microphone. A more elegant development of this method would consist in giving the microphone a continuous rotary or oscillatory movement, while to the abscissa of the cathode-ray tube a sinusoidal or oscillating frequency would be given which would be synchronized with the movement of the microphone by known methods.

Another method of sound analysis adopted recently by Freystedt [50] in the "Audio frequency spectrometer" should be mentioned here. The apparatus incorporates a number of

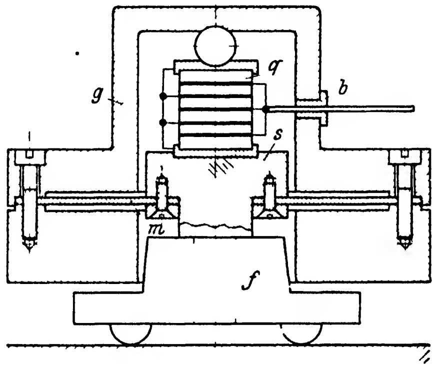


FIG. 403. PIEZO-ELECTRIC SHOCK MEASURING EQUIPMENT

electrical filters covering the entire audio frequency range. The signal under examination is impressed on all the filters simultaneously, the resulting voltage in each circuit being rectified and applied to a condenser. Thus the resulting charge indicates directly the magnitude of the respective frequency component. Since the amplitude concerned is quite insufficient to give an appreciable deflection of the cathode ray, a carrier frequency of $3 \cdot 10^6$ cycles is modulated by these d.c. potentials. The latter after amplification and rectification is applied to the ordinate plates.

For comparative analyses the condensers are connected in quick succession to the modulating unit by means of a rotary switch. The time deflection, on the other hand, is obtained from a steadily varying d.c. potential by a revolving potentiometer driven by the same device. The speed of revolution must, of course, be high enough to give a persistent image.

VI. Uses for Mechanical Measurements

The cathode-ray tube in combination with a suitable coupling device can be used in all cases where mechanical measurements of periodic functions varying at high speeds are to be carried out. There is a multitude of possible uses in this sphere, and a number of typical examples will be given.

Kluge and Linckh use the piezo crystal for electrical vibration

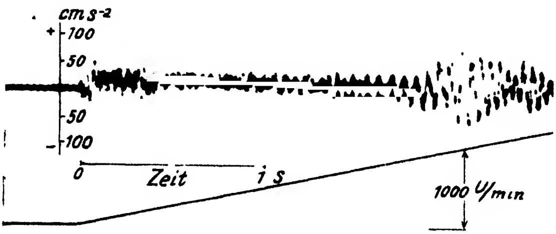


Fig. 404. Fundamental Oscillations on Starting Up a Three-phase Motor

measurements. A pile consisting of several sections of quartz (Fig. 403) is held by a membrane under a certain pressure. This pressure is varied by the vibrations in the set as a result of the movement of a heavy metal housing which rests on the quartz pile. Several pairs of crystals are used to increase the sensitivity.

Fig. 405. Oscillogram of Turbine Oscillations

The intermediate electrodes of the same polarity are connected in parallel. If only one pair of crystals is used and the charge amplified, more accurate measurements are usually obtained. Fig. 404 shows an oscillogram of the fundamental oscillations at the starting of a polyphase motor which was taken with this contrivance, while Fig. 405 shows the oscillograph of turbine vibrations.

Watanabe observed impulses of very short duration with

the pressure-measuring quartz by means of the notched bar bending test (Fig. 406).

Two crystals of opposite polarity laid on one another constitute the notched bar test unit, on which the hammer falls and switches on simultaneously the time deflection of the oscillograph. A single trace of the oscillogram is made.

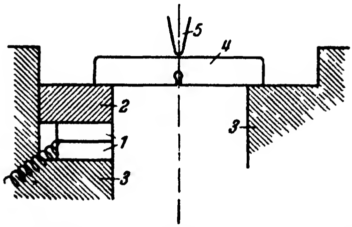


FIG. 406. ARRANGEMENT OF THE QUARTZ FOR IMPACT BENDING TEST

Kluge and Linckh(37) trace the stress of a steel wire statically loaded. The experimental arrangement consists of a thin wire (piano string) hanging vertically, fixed at its upper end and statically loaded by a weight attached to its lower end. The

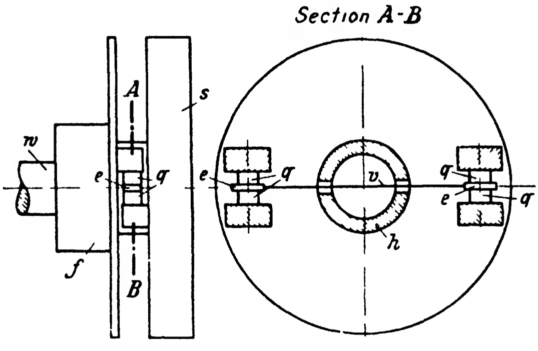


FIG. 407. CONSTRUCTION OF A DEVICE FOR MEASURING ANGULAR ACCELERATION

impulse is produced by a load falling down this wire and giving up its kinetic energy on reaching the lower end. In this way two longitudinal vibrations are produced in the wire, one due to the impulse and the other to the mass, and these are oscillographed by the quartz unit, which is so arranged that the force at the upper end of the wire is transferred direct to the quartz.

Fig. 407 illustrates an arrangement for the measurement of angular acceleration by means of a piezo quartz. The arrangement consists of two rotating bodies rigidly connected together by a hollow shaft. Of these, only one is screwed to the end of the shaft of the machine to be examined. The second, which merely acts as an inert mass, tends to resist the rotation of the first part when this is accelerated by the shaft. The natural frequency is low owing to the rigid connexion to the hollow shaft. A relative elastic rotation between the two is opposed by two quartz units which are fitted to opposing supports

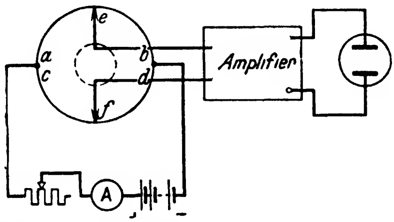


FIG. 408. MEASURING TORSIONAL OSCILLATIONS BY MEANS OF A WHEATSTONE BRIDGE

forming a kind of claw coupling. These units are consequently stressed by a force proportional to the angular acceleration.

Elsässer[38] oscillographs the torque motion by means of the ohmic resistances of a Wheatstone bridge circuit (Fig. 408). The casing of the system in which the torsional vibrations occur carries the circular ring arrangement forming the four arms of the bridge, whilst the indicator is fixed on the driven member. The voltage across the contacts *e* and *f* on the bridge arms, after passing through an amplifier, is oscillographed by the cathode-ray tube.

Kluge and Linckh investigated the cutting pressure in steel during the process of turning. The quartz unit is firmly fixed during operations between the free end of the steel and the lathe support. The arrangement is biased by a potential of 2 volts before measurements are made. By doing this the load corresponding to the pressure at rest is compensated on the one hand, and on the other the apparatus operates on the linear portion of the quartz characteristic.

Gerdien uses a condenser unit as a measuring device, as shown in Fig. 409, for determining cutting pressure. Measurement of longitudinal vibrations can be carried out by the Elsässer

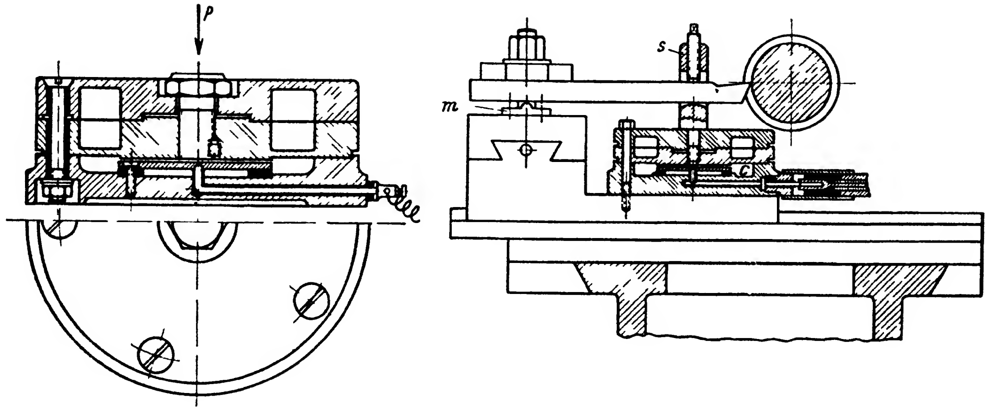


FIG. 409. CONDENSER BOX AND ITS ASSEMBLY ON SUPPORT FOR THE MEASUREMENT OF CUTTING PRESSURE

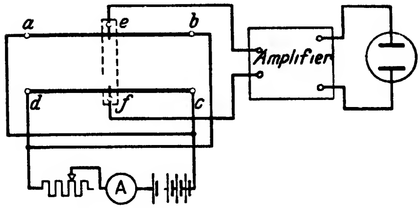


FIG. 410. MEASUREMENT OF LONGITUDINAL VIBRATIONS

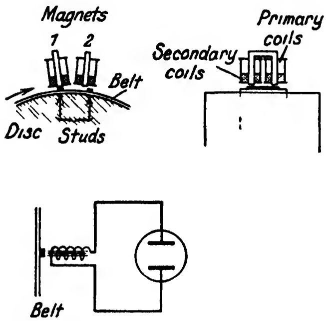


FIG. 411. MEASUREMENT OF THE STRETCHING OF A BELT

FIG. 412. OSCILLOGRAPHIC INVESTIGATION OF THE EFFECT OF TENSILE STRESS ON THE PROPERTIES OF STEEL

process which is exactly analogous to the determination of torsional vibrations with the Wheatstone bridge (Fig. 410).

Steinmetz[39] measures the stretching of a belt by means of a magnetic contact arrangement (Fig. 411). Two narrow strips of wrought iron are riveted to the belt at a distance of 70–100 mm. apart. Closely facing the belt are two electro-magnets, with open iron circuits the same distance from each other. Each of these has two separate windings. The primary windings are excited by d.c. When the iron strips pass the magnetic poles, voltages are induced in the secondary circuits,

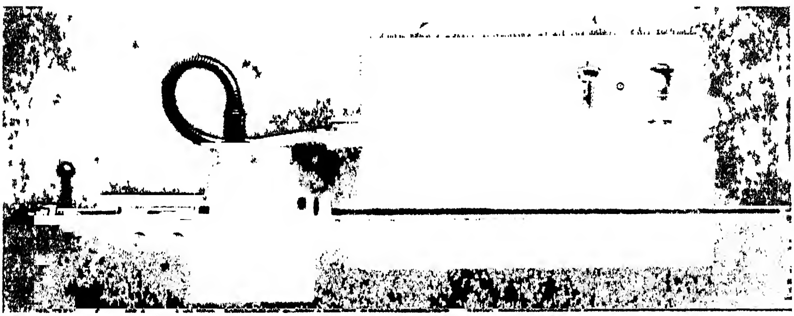


FIG. 413 PRESSURE CHAMBER AND AMPLIFIER FOR MEASURING THE EXPLOSIVE PRESSURE IN A RIFLE BARREL (*Zeiss Ikon*)

and these are oscillographed by the cathode-ray tube. Two oscillograms, one of each induced voltage from the secondary winding of the electromagnets, are obtained. Alteration of the separation of both curves provides a measure of the stretching of the belt. At the same time the rate of revolution of the belt can be deduced from the separation

The oscillogram of Fig. 412, taken by von Schwinning, shows the effect of mechanical tension on the magnetic properties of steel The curve outline is similar to that of a hysteresis loop

VII. USES IN BALLISTICS AND IN CHEMICAL RESEARCH

The cathode-ray tube is frequently used in the measurement of high-speed ballistic processes. In conjunction with the pressure microphone, it serves to determine the course of events taking place during explosions, and when used with contacts or similar accessories to measure the velocity at various points of the trajectory. Fig. 413 illustrates apparatus developed

by Zeiss-Ikon for the measurement of pressure distribution in rifles. On the left is the pressure chamber, the detector of which is constructed in such a way that the spatial dimensions concerned are not appreciably affected. Fig. 414 shows the piezo pressure detector employed.[40] On the left is the pressure element. From the pressure chamber a highly insulated screened cable leads to the mains-operated amplifier,

FIG. 414. PIEZO PRESSURE DETECTOR FOR MEASURING EXPLOSIVE PRESSURE (*Zeiss Ikon*)

which is stabilized by neon lamps. A pressure oscillogram obtained from one shot is reproduced in Fig. 415. The duration of the process is of the order of 0·001 sec. All the important factors involved in the operation can be taken from the oscillogram of the shot, the time of the movement of the bolt, the maximum pressure, the gas pressure when the shot leaves the barrel, the initial velocity, etc. The evaluation of the

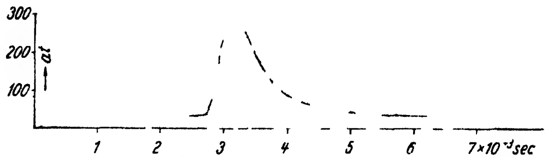


FIG. 415. OSCILLOGRAM OF THE PRESSURE IN A RIFLE BARREL

height of the ordinate in pressure units can be carried out in various ways. The simplest and most exact method consists in calibrating the apparatus empirically by means of a lever press. The pressure element is statically loaded under the press exactly like a copper cylinder, and the corresponding deflection of the cathode-ray tube is traced with the recording chart stationary.

There are many ways of determining shot velocities. The simplest is to allow the shot to pass through two pieces of

thin metal foil forming contact strips at a known distance apart, and to determine oscillographically the time difference between the slits. In place of mechanical contacts, photo-cell devices which have low inertia may be used, the interruption of the light ray being used to produce voltage impulses. To attain the highest accuracy, the points at which measurement is made should be separated by a distance which is large compared with the length of the projectile if the velocity in the direction of motion may be regarded as practically constant, or its average value assumed. One photo-cell and amplifier with good frequency response (see, for example, the television amplifier, Chapter II, page 194 *et seq.*) are sufficient for the light-ray method if the two beams which are required can finally be concentrated on the one cell by means of suitably mounted mirrors. The cell need not be shaded from any constant illumination which has no effect on an a.c. amplifier. In a few cases the method of giving the shot some residual magnetism has been adopted, the shot then being projected through induction coils. If the coil is of small dimensions and has a low inductance, and the amplifier possesses a small time-lag in response and the necessary degree of amplification, then the induced voltages have a rate of change sufficiently great to provide a fairly accurate determination of time at the output terminals.

In combination with correspondingly oriented pressure microphones, the cathode-ray tube serves to determine the pressure variation in several co-ordinate directions in the case of explosions. Also in chemical research, the cathode-ray tube is becoming increasingly popular for the investigation of rapid reactions. The changes of pressure during a reaction, the variation of light emission or absorption, or other changes which may occur, are recorded by the cathode-ray tube.

An arrangement for the oscillographic investigation of the explosive reaction between equal volumes of hydrogen and chlorine, is illustrated in Fig. 416. A ray of light from a lamp (Uviolglass), whose intensity is insufficient to bring about chemical action, passes through the reaction chamber on to the photo-cell. The reaction vessel and the bulb of the photo-cell are also of Uviolglass. In addition a dark filter is interposed in the path of the ray. As long as the reaction has not started, there is a strong absorption of light due to the chlorine. The change in absorption which takes place after the reaction sets in is traced oscillographically. The reaction is started by a spark discharge.

This is controlled by the switch S_2 and the electrical time deflection is started simultaneously. The switch S_1, just released, opens the aperture of the recording camera. The spark gap is arranged so that as far as possible only a small part of the light from the spark reaches the photo-cell.

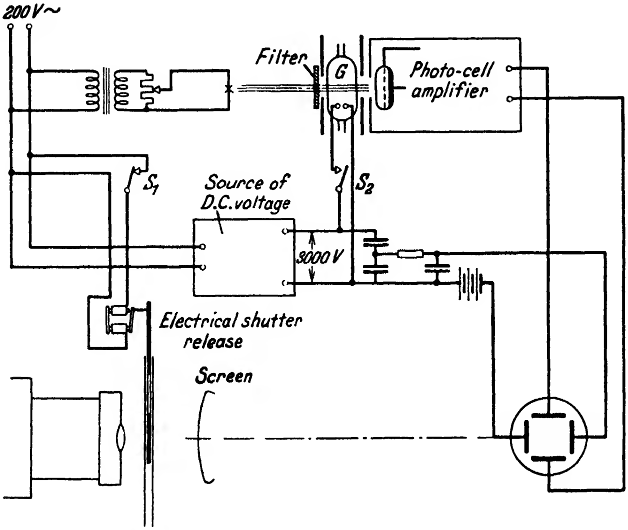


FIG. 416. ARRANGEMENT FOR OSCILLOGRAPHIC EXAMINATION OF GAS REACTIONS

The cathode-ray tube has also been used for measuring rapid changes in the velocity of flow of gases.[41]

VIII. MEASUREMENTS ON INTERNAL COMBUSTION ENGINES

The cathode-ray tube is used for measurements on internal combustion engines, to photograph time-pressure curves, and to oscillograph knocking noises which take place. Measurements of vibration, particularly the determination of the mechanical resonance of individual component parts, are carried out with the quartz crystal measuring equipment already described. The recording of sudden stresses due to shock, particularly surface stresses in various directions, are further investigations. Measurements on rail bonding on

railway tracks, and the pressure of the current collector against the rail or wire, are also carried out by the cathode-ray tube.

The pressure-time curve in cylinders of internal combustion engines has been photographed by Kluge and Linckh[42] with the quartz pressure unit already referred to. Photography in ordinary engines is greatly simplified by a new piezo element combined with a plug made by Zeiss-Ikon, Dresden. In photographing these curves the sparking point can be marked on the curve simultaneously by tapping from the discharge circuit a voltage of about 10, i.e. less than 1 per cent of the striking voltage, and applying it to the brightness control electrode of the oscillograph. The instant of firing is indicated as a light or dark spot, according to the phase, on the time-pressure curve. Marking the dead-centre point, and for that matter any desired point of the cycle of operations, can be carried out in the same way.

In such photography, the cathode-ray tube offers the further possibility of obtaining the curve as a stationary figure on the luminous screen if a time discharge synchronous with the operating period is applied to the second pair of deflecting plates. Automatic synchronizing is recommended if the number of revolutions of the motor is variable. Synchronization is most simply attained with a rotating contact on the crankshaft. This revolving contact is either inserted in the discharge path in place of the neon lamp, or it is used to apply periodically a potential to the control electrode of a neon lamp.

For the investigation of the details of operation of motors and the effect of various fuels, the analysis of knocking noise in combustion engines carried out by Wawrziniok[43] in collaboration with Martin, by means of the cathode-ray tube, is of particular importance. In this connexion reference should be made to publications[44] by the same authors which are particularly interesting and deal with experiments on simultaneous recording of several processes using two oscillograph tubes. Fig. 417 shows a picture of the complete apparatus. By means of a freely suspended condenser microphone, the noise emanating from the engine is picked up. At the same time spurious noises are excluded by connecting a short rubber tube between the microphone housing and the engine cylinder. The photograph of the image of the noise is obtained by the cathode-ray tube, preceded by an amplifier. The connexion can be made either through a pure ohmic resistance coupling or through

an inductance which acts as a distorting coupling, and as a short circuit to lower frequencies. The point of maximum amplification is displaced into the region of the knocking noise

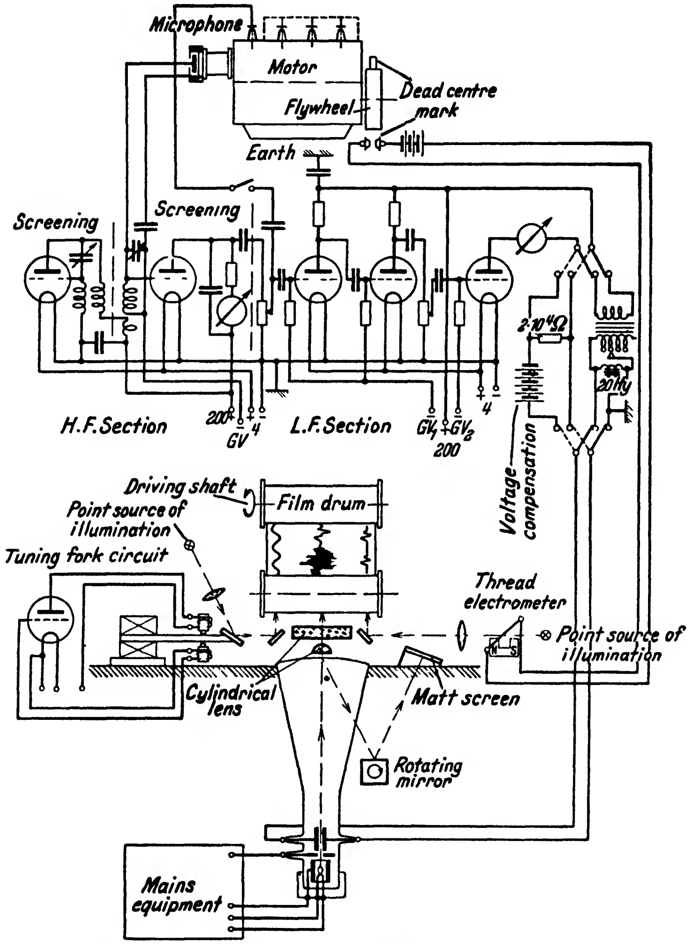
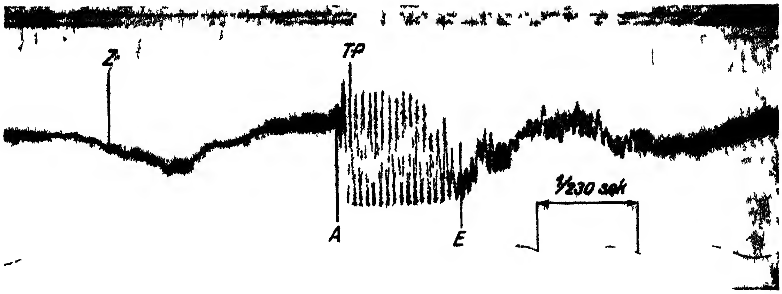
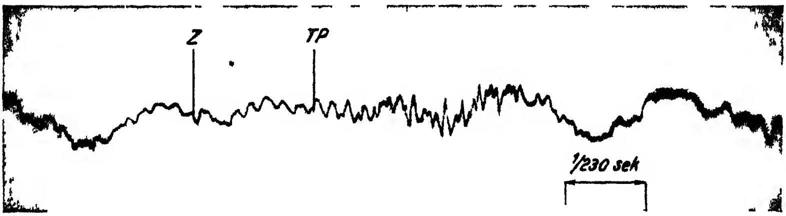


FIG. 417. WAWRZINIOK APPARATUS FOR MEASURING AND INVESTIGATING "KNOCKING" NOISES IN INTERNAL COMBUSTION ENGINES

frequencies by the selective inductive coupling, and the unwanted lower frequencies are excluded from the total noise. For time marking, the image of a vibrating tuning fork is continuously photographed on the film of the oscillograph, and this

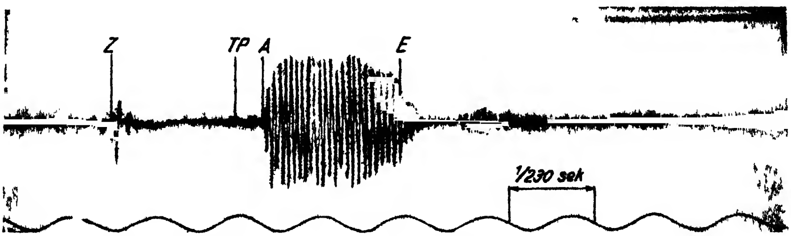


Speed 600 r p m Ignition advanced 40°
Fuel benzine Frequency of knocking noise 3 360 per sec

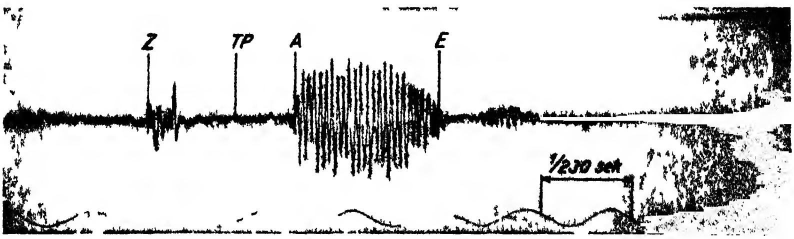


Speed 1 000 r p m Ignition advanced 40°
Fuel benzol

FIG. 418 OSCILLOGRAM OF ACOUSTIC VIBRATIONS IN AN INTERNAL COMBUSTION ENGINE



Speed 1 000 r p m Ignition advanced 40°



Speed 1 000 r p m Ignition advanced 25°

FIG. 419. OSCILLOGRAMS OF KNOCKING NOISES UNDER DIFFERENT CONDITIONS OF PRE-IGNITION USING BENZINE

appears on the lower edge of the oscillogram as a sinusoidal wave. An additional disturbance of short duration in the amplifier due to the sparking current effects the marking of the sparking point. It is noticeable on the oscillogram as a slight rise in the line. The dead centre mark is made at the upper end of the oscillogram by a thread electrometer which is operated through a short circuit contact from the flywheel. The striking point mark can in this case also be carried out by influencing the Wehnelt cylinder. Time deflection is effected by mechanical movement of the photographic film. Figs. 418 and 419 show several oscillograms photographed with this device. These show the effect of the fuels used and the effect on the knocking noise of advancing the ignition. It can be seen that benzol, as distinct from benzine, shows no knocking noise and that, on the other hand, as the ignition is advanced the amplitude of the knocking noise increases.

IX. Uses in Medical Research

Photography of cardiac sounds and currents due to nerve actions by means of the oscillograph has already become a classical example of its use in medical research and practice. Oscillographic photography brings about progress in two ways. The curve obtained shows direct evidence of the nature of the noise which takes place at different times. By means of the curve outline, the doctor can form a definite opinion of the changes in noise which take place. Furthermore, the record shows characteristic differences in noise which are not detectable by direct observation. By using suitable microphones and amplifiers, very low frequencies below the audible limit can also be recorded.

Loop oscillograph devices are used for photographing cardiac noises and currents due to the heart's action, and only quite recently has the cathode-ray oscillograph found a sphere of utility here. A type of mobile cathode-ray electro-cardiograph, which includes the oscillograph equipment, the necessary amplifiers, and sources of current, is illustrated in Fig. 420. Electro-cardiograms traced by this equipment are reproduced in Fig. 421. As a result of the ability of the equipment to withstand overloading, no damage will be done to it by the unforeseen increase of the sound under examination which is capable of giving rise to strong currents.

For instance, with the equipment illustrated, it has been possible to investigate the effect of the electrical shock to a person under examination with simultaneous electro-cardiography. Special screened electrodes, suited to the conditions of the experiment and connected up to the input side of the amplifier, are used to pick up the voltage. The form of the microphone depends also to a great extent on the nature of the problem under consideration, the microphone membrane is

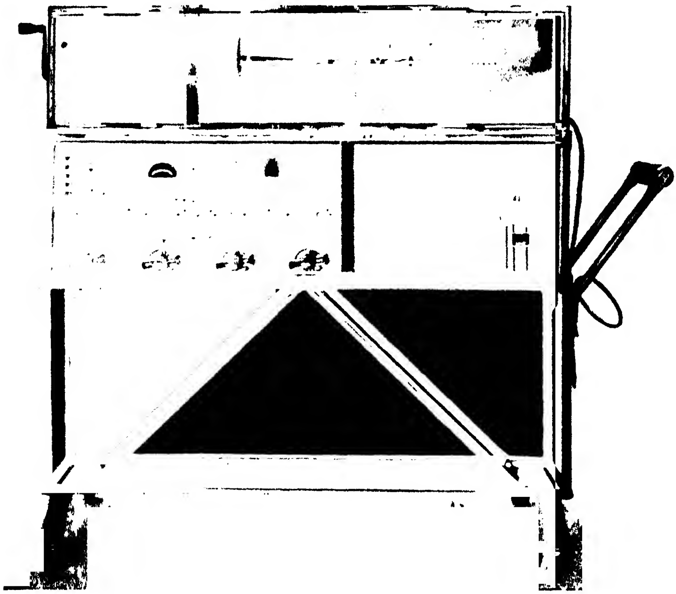


FIG. 420 OLD FORM OF CATHODE-RAY ELECTRO-CARDIOGRAPH
(*E Leybold*)

coupled directly to the zone under investigation. Of the more modern cathode-ray cardiographs the Cossor-Robertson deserves special mention. In this, by reason of the special construction of the amplifier, a direct-coupled amplifier with its well-known disadvantages is avoided without affecting the low-frequency components in the cardiogram. More recently an endeavour has been made to record the currents in three leads simultaneously by a threefold tracing system. Besides the investigation of heart beats, on which there exists a vast amount of

literature,[47] the tracing of lung noises is important. The tracing of lung noises is not technically very simple, because they are very weak compared with sounds from the heart. Greater amplification and special design of the microphone are

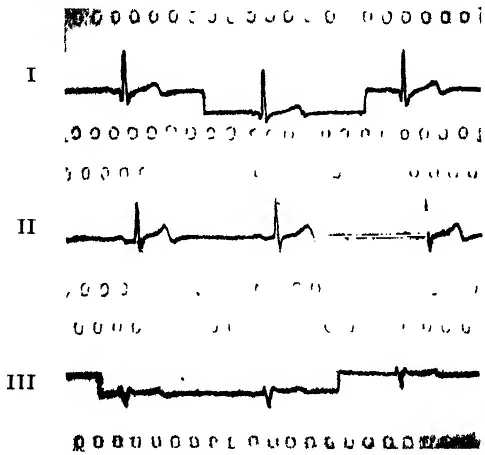


FIG. 421. ELECTRO-CARDIOGRAMS RECORDED WITH A CATHODE-RAY TUBE

necessary to exclude the heart noises which occur at the same time. The frequency components of heart sounds are mostly quite low, while those of lung noises are high. By accentuating the high at the expense of the low frequencies, it is possible to

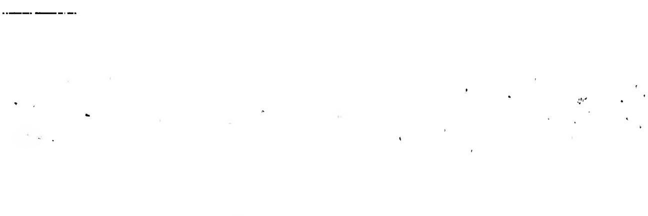


FIG. 422. OSCILLOGRAM OF A RESPIRATORY NOISE (BRONCHIAL RESPIRATION)

produce voltages which are representative of lung noises alone. Fig. 422 illustrates the oscillogram of a respiratory noise. As shown by other workers,[51] valuable conclusions can be drawn from the oscillograms of various breathing noises (bronchial and vesicular noises, deep breathing, rattling noises, etc.).

The cathode-ray oscillograph is of great interest in physiological research. Here the small currents and voltages which occur in animal and human organisms, in the nerves and muscles, are of interest. Investigations are extended to include the way in which the magnitude of the voltage and the outline of the curve depends on mental impressions, thoughts, voluntary actions, etc. The process in the nerves and muscles is such that a charge which is negative relative to an unexcited point, traverses the nerve or muscle. The problem consists of measuring with the oscillogram the relatively slow progressive transient.

F. Scheminzky[45] recently published a detailed example of acoustic measurements with the cathode-ray oscillograph in physiology. The same author[46] discusses in a comprehensive treatise the oscillography of nerve reaction currents with the cathode-ray tube. The main difficulty in recording these is the necessity of using direct-coupled amplifiers, owing to the extremely low frequency components which are present. Detailed hints have already been given above (Chapter II, page 206) about improvements in construction of such an amplifier, and also the method of carrier current amplification or of a.c. current amplifiers with symmetrical stages which are most suited to this purpose.

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CHAPTER IV

THE CATHODE-RAY TUBE AS AN OPERATING UNIT

THE development of the cathode-ray tube from being solely a laboratory instrument to a compact, handy unit which could be always available for use, signified progress in directions other than that of measurement and opened up a further sphere of usefulness for it as an operating device.

I. USE IN SOUND-FILM RECORDING

In 1921 Vogt, Engl, and Massolle (1) suggested the use of the cathode-ray tube in sound-film photography in connexion with talking pictures, but Tobis later dropped the idea. The first practical results of which use could be made, and in which sufficient blackening of the photographic material took place, were achieved by Breusing-Hartel in January, 1930, with the author's tubes. Just before this, the work of Friess had begun. Lately, the development of high-vacuum receiving tubes has enabled considerable progress to be made resulting in a great increase in stability, life, light intensity and sensitivity of control.

1. **Fundamental Considerations.** The use of the cathode-ray tube for sound photography has the advantage of needing only a very small output for its control. The power consumed by the amplifier, which is a disadvantage, particularly in portable sets, is reduced to a minimum. In most cases one or two stages are sufficient to ensure adequate reserve of sensitivity to deal with all requirements during recording, i.e. for the microphone and its associated circuits, and for correction of frequency characteristic in speech or music. In cases where speech occurring directly in front of the microphone is to be recorded, the control voltages produced by very efficient microphones (e.g. Reisz high current microphone) are great enough for complete control of the film without amplification.

A further advantage in favour of mobility is the low power consumption from the supply—of only a few watts. Finally, the independence of frequency in the low range—an obvious

condition for this being a fluorescent screen sufficiently free from after-glow—is also to be considered an advantage in this kind of photography.

2. **Variable Area and Variable Density Recording with the Cathode-ray Tube.** There are two different processes for sound recording, and the principles of both are shown in Fig. 423. Directly behind the screen of the sealed-off tube which traces the record, a slot which is as narrow as possible is fixed level with the fluorescent stroke. If the intensity of the ray of the tube is modulated, then the film which passes across

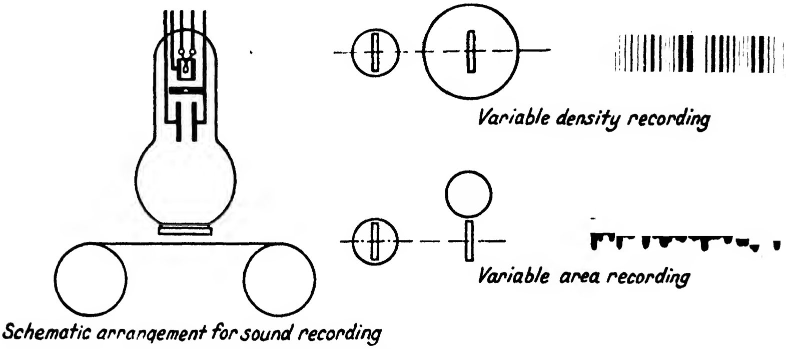

FIG. 423. DIAGRAMMATIC REPRESENTATION OF SOUND RECORDING WITH THE CATHODE-RAY TUBE FOR VARIABLE AREA AND VARIABLE DENSITY PROCESSES

the slot is illuminated with a variable amount of light. This is known as variable density recording. If the amount of fluorescent light passing through the slot is varied by a side deflection of the ray, and not by variation of its intensity, then variable area recording results. Both processes are common practice to-day. As the photographic advantages expected from the variable area process have not materialized completely, the importance of the variable density method tends to increase. In both methods there is, for photographic reasons, a limited range of working. Attempts have been made, therefore, to combine them. Such a combination record is quite easy to obtain. Before the special considerations of controlling the fluorescent light for the purpose of sound photography are discussed, let us consider the various methods of forming the image, as the best method of modulation depends partly on this.

3. **The Formation of a Narrow Tracing Stroke.** In order that the upper audible frequencies may be traced without amplitude distortion at the given film velocity of 46 cm. per sec., the width of the tracing stroke on the film[(2)] must not be greater than about 15–20 μ. This applies equally to variable-density and variable area recording. As it is difficult to secure such a narrow slit which is at the same time uniform—even slight dirt or dust particles suffice to block up the aperture—the method of projecting on to the film a slit of larger dimensions which is reduced optically has been used in sound recording with Kerr cells, neon lamps, etc. The greater part of

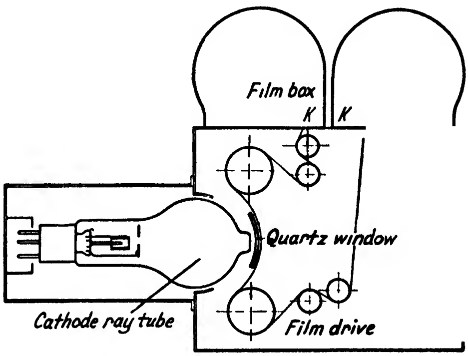

FIG. 424. SOUND RECORDING WITHOUT ANY OPTICAL SYSTEM

the light available is lost in the process of optical projection. As the cathode-ray tube did not, at any rate at first, give any reserve of illumination, it was important to avoid projection by optical methods. A method of doing this, and formerly exploited successfully by Breusing, was employed for the recording camera shown diagrammatically in Fig. 424. Between the fluorescent screen of the tube and the film is a quartz double-meniscus lens over the convex and highly polished side of which the film passes. On the contact surface between the two lenses an opaque silver layer is fixed, and on this there is a gap of 12 μ in width. The distance of the gap from the film is about 0·15 mm. and is very small compared with the distance between the slit and the fluorescent screen, so that a sufficiently sharp image of the slit is produced from the fluorescent spot or stroke, which is oriented in the direction of the slit. Attempts have been made several times to protect the slit from

dust by a thin film of collodion. More recently it seems that even with the cathode-ray tube, general practice has been to form an image of the stroke by optical reduction. For this

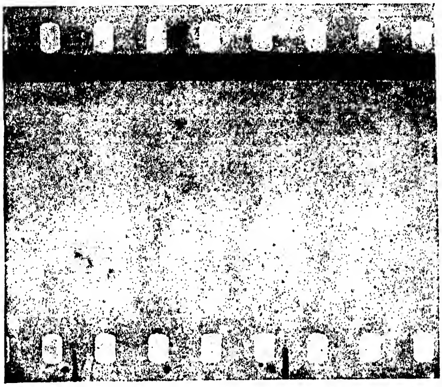

FIG. 425. VARIABLE DENSITY RECORD OBTAINED WITH CATHODE-RAY TUBE

purpose, small but very powerful optical condensers, parabolic mirrors, cylindrical lens systems, etc., in many and varied

FIG. 426. VARIABLE AREA TRACING WITH CATHODE-RAY TUBE

forms have been used. The reproduction of variable area and variable density records obtained several years ago (illustrated in Figs. 425 and 426: sound recording by Friess) prove that even when optical projection is used the amount of light

available is quite sufficient for the control of normal positive and negative stock. In the case of these tracings, the anode voltage was of the order 2 000–2 800.

4. **Modulation of the Fluorescent Light.** The fluorescent light should be capable of modulation to such an extent that at least the whole linear range of the gradation curve of the negative material is covered. The control should be linear over such a limited range. A change in position of the luminous source, which may give rise to errors, and frequency modulation must be avoided. The various methods of intensity control usual in sound recording are given below.

Fundamentally all the methods for modulating the ray intensity given in the first part of the book can be considered for intensity control. Although a change in position with voltage modulation can be easily avoided if the ray is not subjected to a deflecting field, anode voltage modulation has not attained any importance in view of the fact that control voltages of the order of 1 000 volts are necessary. In practice, current modulation is employed. Control is made through the Wehnelt cylinder or similar electrode fixed near the cathode for varying the brightness. The control voltages required decrease as the slope of the control characteristic becomes greater. At first, deflected light control without current modulation was carried out by deflecting the spot through a slit similar to the variable area process mentioned above. Compared with the method of variable area control given in Fig. 424, the difference consists in the fact that the direction of the fluorescent stroke is perpendicular to the direction of the slit. In this kind of brightness control it is desirable to give a bias so that operation takes place outside the zone of origin distortion in order to secure a linear sensitivity curve, and obtain high deflectional sensitivity. The kind of intensity control mentioned above has not attained any great importance on account of the greater length of tube, greater disturbance due to external stray fields, and the ease with which over-loading can occur. The control range, like that of a Kerr cell, is not good enough, i.e. if very much overloaded brightness will diminish.

Greater efficiency is secured more easily if the fluorescent spot has a shape similar to the narrow tracing stroke required on the film. There are various ways of giving the light spot an extended shape. The ray can be allowed to spread over the luminous screen, a strip of light being obtained by a suitable

mask, or it can be flattened out by very intense spatially concentrated magnetic fields. The second method has the advantage that change in position under the influence of control of the illumination cannot easily occur even with the badly centred older systems. The position of the ray is held magnetically. By adjusting the magnetic field the fluorescent stroke can be easily varied, and by altering the magnetizing current its width can be changed. This method, developed in practice by Friess, has the advantage that the formation of the stroke is not accompanied by losses which occur when masking by an aperture is employed; on the contrary, the entire energy of the rays is utilized Flattening out the ray has been often done by a combination of magnetic and electrical methods. Deformation of the spot by means of high or medium frequency magnetic or electric deflection has also the advantage that strokes of uniform intensity are produced along their entire length. This is particularly the case if ray deflection is effected by a "saw-tooth" oscillation, and not a sinusoidal oscillation. It should be noted that in the case of older gas types the deflection frequency should be low (10^5 cyc.) if the effect of gas-focusing is to be maintained. The intrinsic value of the light intensity naturally decreases owing to the distribution of the ray energy over a larger surface. At first this decrease, however, does not occur, or at any rate

FIG. 427 THE AUTHOR'S SOUND-FILM RECORDING TUBE WHICH HAS A LINE SOURCE AND TWO ELECTRON-OPTICAL LENS SYSTEMS

is very small on account of saturation and fatigue of the fluorescent screen. In practice, fluorescent strokes of 1 cm. length with a width of $\frac{1}{2}$–1 mm. are usual. If alteration in position which is small compared with the width of the stroke takes place, it is advisable to make the stroke wider by a further deflection in a direction perpendicular to the stroke. This leads to a decrease in the luminous intensity and should, therefore, be kept as low as possible (deflection amplitude 1–2 mm.).

Recently high-vacuum tubes have been adopted almost universally. Fig. 427 shows the construction of a tube with two electron-optical cylindrical lens systems. The grouping of the accelerating electrodes, as also the electron-optical

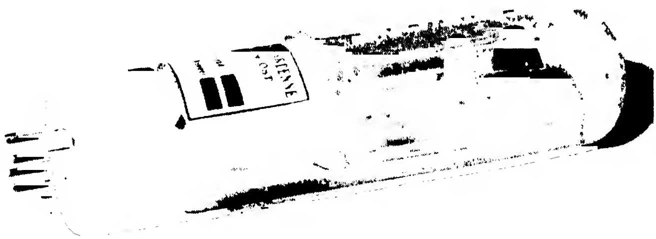

FIG. 428. HIGH-VACUUM SOUND FILM RECORDING TUBE WITH LINE SOURCE FOR SUPERIMPOSED INTENSITY AND AMPLITUDE RECORDING

path of the ray, corresponds in essentials to the tube construction of Fig. 21, except that the slotted discs have taken the place of circular apertures. The circular form of electrodes has been chosen to obtain extensive co-ordination of the field structure for various radial directions.

Proper centring of the system definitely ensures that the intensity of the fluorescent stroke appearing on the screen can be evenly controlled. Voltage changes of 10–15 volts suffice for light-dark control. An indirectly heated cylindrical cathode provides the electron emission. Fig. 428 illustrates another type of tube for sound-film photography. In this, flat or only slightly curved electrodes are employed. With this system the length of the fluorescent stroke is controlled at the same time as the intensity in such a way that dark adjustment gives a short and bright adjustment a long fluorescent stroke. As amplitude change occurs in correct phase, therefore, this reinforces pure

intensity control. The fluorescent strokes themselves are with these two types of tubes very narrow (< 1 mm.). Special magnets for adjustment are unnecessary, since the position of the stroke is constant. Special mention must be made of the fact that brightness control does not cause any change in position of the stroke. The anode current of the high-vacuum tubes described reaches values of 0·5 mA. or more, so that relatively low anode voltages suffice to obtain the necessary light intensity. Since screens of high secondary emission are used and

FIG. 429. ELECTRODE SYSTEM OF A FRIESS TUBE FOR VARIABLE AREA RECORDING

the large surface anode is placed near the screen, there is a very rapid and intense back current of electrons, and therefore disturbance by screen overloading is avoided. To obtain variable area tracing it is again necessary to aim at getting a long fluorescent spot which more or less fits the slit area as far as possible. Sometimes the deflection voltages employed in creating the stroke are modulated in order to trace sound without the aid of a slit. That such modulation even with saw-tooth oscillations—generally more satisfactory—is entirely successful has already been indicated in the chapter on electrical time deflection (Chapter II, page 308).

A disadvantage of this modulation process is that, except when complicated compensating circuits are used, the density

decreases as the amplitude increases, because the ray energy is distributed over a greater surface. Within certain limits this fault can be reduced by over-control on exposure. The method indicated at the beginning of allowing a fluorescent stroke of uniform luminous intensity, more or less to fill the slit, is more generally known. The deflection of the stroke takes place before the ray is flattened out, so that the means of deflection can be brought as close as possible to the ray, to use the smallest control voltages or currents. Fig. 429

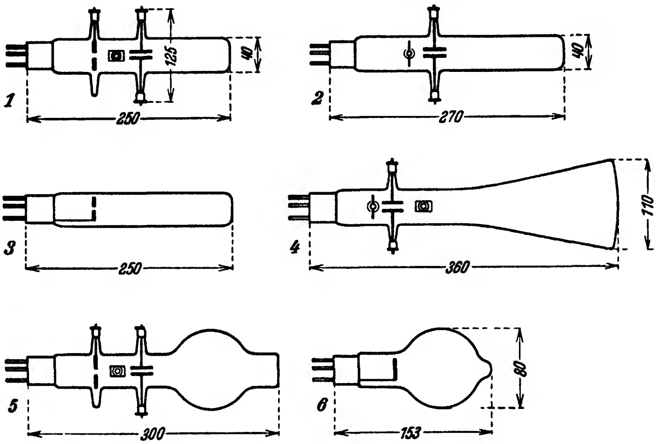

FIG. 430. ASSEMBLY AND DIMENSIONS OF COMMERCIAL TUBES FOR SOUND RECORDING

illustrates such an electrode arrangement. Directly behind the anode a long narrow pair of plates is fitted, and these provide relatively high deflection sensitivity. The modulating voltage is applied to this pair of plates. Behind them is a second pair of plates in the same direction but of lower sensitivity (shorter plates with greater distance between them). A medium frequency voltage is applied to this pair of plates to give the sweep.

The formation of the stroke can be effected just as well by external magnetic deflection. Simultaneous connexion of low and high frequency to one and the same pair of plates —suitably designed chokes preceding them—has also sometimes been used. In the preceding pages only those methods whose practical use is well known have been selected from many possible applications. Many other possibilities result

from the combination of other forms of construction and auxiliary circuits already mentioned in this book. Particular importance in future may be attached to sound photography by high-vacuum electron tubes which can be influenced by external means of focusing, and have therefore an additional independent control.

5. **Practical Construction of Photographic Units.** Sound-film recording can be carried out successfully with ordinary oscillograph tubes. Nevertheless, it was not long before smaller forms of construction were adopted in order to reduce the length of the recording equipment. Fig. 430 gives the dimensions of

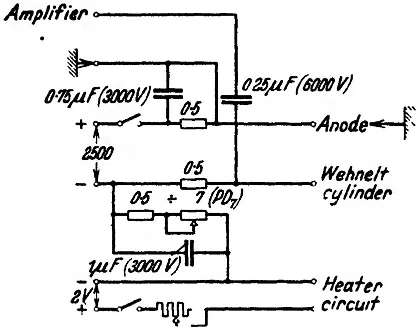

FIG. 431. OPERATING CIRCUIT FOR SOUND RECORDING WITH AN OLD TYPE OF GAS-FILLED TUBE

various old types of sound-film tubes which can be used more or less universally, i.e. which have two or more deflecting plates. Cooling contrivances are unnecessary with such ray intensities, as the glass is never exposed to high temperatures. The life of modern high-vacuum tubes for tracing sound is between 100 and 1 000 hours according to the actual load. As special occasions may require, the tubes are fitted with electron-optical systems which give rise to sharp line- or spot-shaped images.

The properties of the two types of high-vacuum tube which in recent times have become popular for practical purposes have been fully discussed above. The dimensions are also sufficiently clear in the illustrations. With these tubes without deflecting plates the earthing of the current source will be made at the cathode, in order to work without high insulation in the brightness control circuit. As with high-vacuum tubes used for measurement, so in the case of sound-film photography

tubes, the use of a lens voltage of adjustable range is necessary to get the sharpest focus for the stroke. Suitable mains operating circuits have been given previously in Chapter II, page 186 *et seq.*

Fig. 431 illustrates a circuit for operating older or gas-filled tubes for sound-film photography having one pair of deflecting

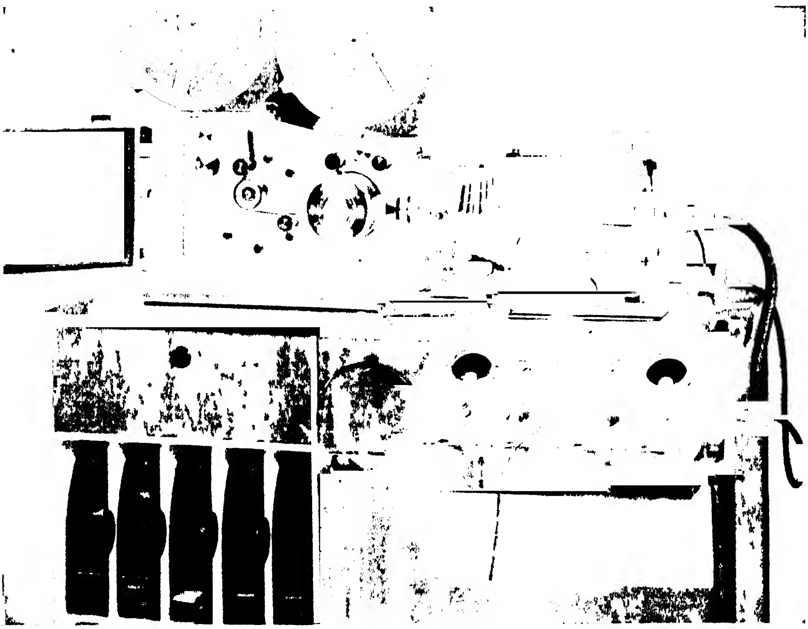

FIG. 432 TRANSPORTABLE CATHODE-RAY PHOTOGRAPHIC UNIT (*Friess, A.G.*)

plates. In the case of indirectly heated cathodes, heating by a.c. is permissible even with the restrictions imposed by sound-film photography. Of course, batteries as sources of current are necessary for portable sets or when the above-mentioned h.f. mains-connected equipment is employed. The latter requires only a small anode battery, possibly also an additional heating accumulator, and is therefore admirably equipped as a portable set. The details of the construction of the tracing camera by Breusing Lignose have already been given at the beginning of this section. Fig. 432 illustrates the construction of a complete portable tracing equipment by Friess, A.G. At the top left

corner is the amplifier fitted with the various control instruments, and the control for the high-vacuum tube. A screened cable is led from this point to the cathode-ray tube on the right, which is movable, and is mounted in front of the projection condenser. The sharpness of the stroke can be controlled during tracing by the aid of a simple observation lens, and the modulation can also be controlled simultaneously in the same way.

The arrangement of the tracing and observation systems in

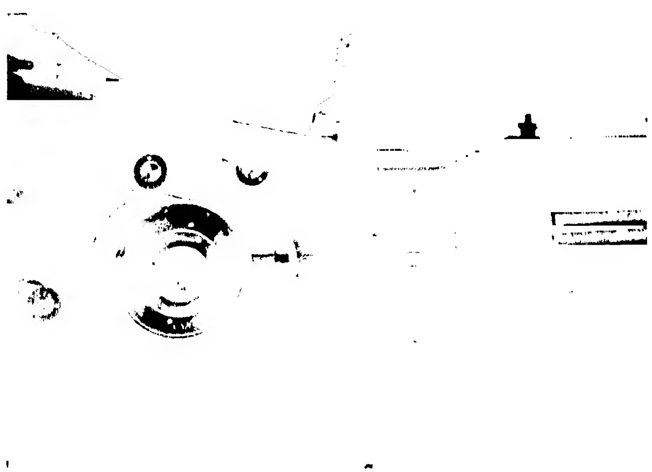

FIG. 433. ARRANGEMENT OF THE OPTICAL REPRODUCTION SYSTEM FOR OBSERVATION OF SLIT IMAGE DURING RECORDING (*Freiss, A.G.*)

the Friess apparatus is shown in Fig. 433. The accumulators and batteries are housed in the lower part of the carrier.

II. USE IN TELEVISION TRANSMITTERS AND RECEIVERS

As long as the principle of splitting up the picture into a number of points and their subsequent reassembly—i.e. the raster process—is used, television will remain a typical example of high-speed high-frequency energy conversion. The forecast made with emphasis by F. Schröter[3] some years ago that television would be possible by purely electronic methods without motors, discs, or mirror wheels, has been confirmed. The line of development of television, taking the latest results into consideration, is following that taken by h.f. oscillatory

circuits in other spheres of application. The tendency to replace mechanical devices by high-vacuum electron tubes which are practically free from inertia, or gas-discharge tubes with very little inertia, is always in evidence, as the technique of amplifiers, d.c. rectifiers and converters has shown.

1. **Fundamental Principles.** The cathode-ray tube has all the properties necessary for the maintenance of the development of television progress. Its fundamental advantages are—

1. Elimination of all mechanical drives and therefore perfectly silent operation.
2. Only very small power is required for deflection and modulation, so that the power consumption for amplification and synchronization is always small.
3. The position of the ray and its intensity are not controlled by separate devices as in mechanical units.
4. As a rule, there are no absorption and aperture losses due to complex optical systems.
5. Ideal spatial light distribution of the screen image.
6. The ray output can be used without screening, i.e. without loss in the production of fluorescent light.
7. As a result of the freedom from inertia of the ray, methods of control which enable sudden changes in velocity to be made can also be employed.
8. The uniformity of the picture raster depends only on the approximate shape of the deflection curve instead of on the precision and finish of expensive mechanically-operated components.
9. It is possible to scan with varied numbers of lines and picture frames by simple alteration of the design.
10. The change-over to other scanning systems can be made by the addition of a small switching circuit.
11. The tube is constructed of simple and cheap components.

2. **Historical Survey.** The advantages enumerated were to a great extent recognized early in the development of tubes. Rosing, with considerable foresight, suggested the cathode-ray tube in receiving equipment as early as 1907. Suggestions equally prescient are associated with the names of Campbell-Swinton, Nicolson, Dauvillier, Dieckmann, Sabbah, and Skaupy. Besides the suggestions of the above-named inventors, there is a large number of publications containing other ideas which are for the most part of little practical importance, and are, therefore, omitted here. Almost all the earlier suggestions

patented were never put into practice. The technique of amplifiers, photo-cells, and cathode-ray tubes had not advanced sufficiently for this to be done. The first tentative experiments were carried out in 1924 by Dauvillier, and a little later by Dieckmann who had already shown silhouettes of simple geometrical figures at the Munich Trades Exhibition. Such work had perforce to remain as first attempts because only the knowledge then in existence could be employed. The development of the cathode-ray tube receiver according to plan was tackled practically in America by Zworykin, and simultaneously in Germany by the author. In both cases the individual components were subjected to investigation and improvement before work on the combined equipment took place. Zworykin paid particular attention to the development of photo-cells and cathode-ray tubes, whilst the author turned to the development of aperiodic amplifiers and cathode-ray tubes.

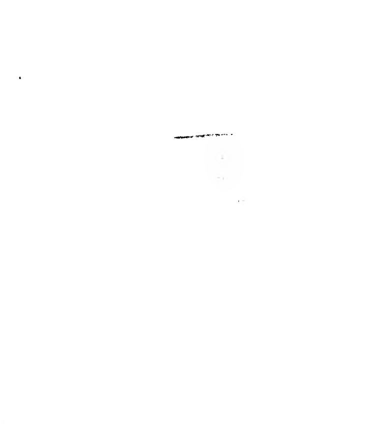

FIG. 434. TELEVIZED PICTURE ON THE FLUORESCENT SCREEN (DECEMBER, 1930)

In a lecture in January, 1930, proof was given by a demonstration that the cathode-ray tube, as far as spot sharpness and brightness were concerned, was a fully developed laboratory product, capable of producing a well illuminated life-like picture. Thereafter the problem of controlling the brightness without change in position was given attention until it appeared that the united experiments would lead to satisfactory results very quickly. In the meantime, Zworykin obtained the first picture, still using a sine wave scanning curve. The first evenly illuminated moving pictures with uniform spot sharpness, the quality of which equalled or excelled the pictures obtainable at the same time by mechanical means, were produced by the author between November, 1930, and April, 1931. From the very beginning of the experiments, line-scanning by saw-tooth oscillation circuits having a linear voltage rise was adopted, as

this was shown to be far superior to line scanning with sine wave voltages. Fig. 434 illustrates the first photographed fluorescent screen picture with half-tones, which was shown in December, 1930. A few months later it was possible to exhibit to a large audience motion pictures of the quality shown in Fig. 435, an unretouched photograph of the fluorescent screen. This picture corresponds to about 9 000 picture points, and shows precision control of the illumination over the whole field. Furthermore, it shows very strong contrasts with good

FIG. 435 UNRETOUCHED PHOTOGRAPH OF A FLUORESCENT SCREEN PICTURE (*von Ardenne, April*, 1931)

production of half-tones. In addition, disturbance of the picture by origin distortion has been avoided. An intensive development of the cathode-ray receiver began in many places, partly as a result of these facts which were made known by lectures. In this connexion the work of Hudec (Reichs-postzentralamt), who paid special attention to scanning and synchronizing with discharge tube circuits, and who in the autumn of 1931 showed motion pictures with separate synchronization, should be mentioned (Radio Exhibition, 1931). Television by cathode-ray tubes has been considerably advanced by systematic work by the Telefunken Co., carried out under the direction of F. Schröter. The experimental work of the Telefunken Co. on complete units began practically simultaneously with that of Hudec. The first public

demonstrations of high definition were made at the Radio Exhibition in 1932 (about 10 000 picture points and separate synchronization).

After it was recognized from the author's experiments in the spring of 1931 that the limits of quality were determined primarily at the transmitting end, and means for the anticipated inauguration of high voltage oscillograph technique as a further effort to solve the problem were not available, the author turned his attention to velocity modulation suggested by Thun. Demonstration of low definition pictures by velocity modulation were carried out in the spring of 1931. Pictures of a quality approximating to that obtained by intensity modulation were shown at the end of 1931.

In the period which followed, the interest in television and the number of physicists at work on the solution of the problem greatly increased. By systematic and detailed work, many of the minor problems associated with it were solved. In particular, high-vacuum television tubes, synchronization which gave stable operation with wireless reception, and ultra-short-wave transmitters and receivers which cover the required wide frequency bands, came into being. The forecast that the standard of efficient transmitters, which until recently corresponded to about 40 000 picture points with 180 line per sec. scanning and a picture repetition of 25 per sec., would be exceeded, has now been proved by the present-day transmitters. Modern valves as well as discharge circuits and receivers are so far developed to-day that they should be able to cope with further increase in the number of picture points.

3. **Cathode-ray Television Transmission and Picture Scanning.** The cathode-ray tube was also suggested many times in its early stages for transmission purposes (Schoultz, Zworykin, Sabbah, Farnsworth).

The basic idea of all the older proposals was that in place of the luminous screen there should be a photo-electric mosaic on to which a picture was projected, and this was to modulate a carrier wave by the scanning cathode ray. The suggestions for attaining this end were very varied, and were not entirely faultless either electrically or in accordance with the quantum theory.

The knowledge of how to produce the necessary photo-active films or raster elements with the desired uniformity, and how to eliminate technical troubles associated with the vacuum,

which were still not entirely overcome, has only recently been acquired. In addition, many of the old suggestions only became practicable as a result of modern electron-optics. Among the various processes, one deserves special mention, since by it an integration of the light impression throughout the whole duration of the picture is possible as distinct from the usual scanning process in television. Only by the use of the integration method employed with the iconoscope, which has been developed by Zworykin [(19)], is it now possible to transmit pictures of normal brightness. Great as is the undoubted importance of this and similar processes in the future development of television technique, it is not intended in this section to go further into the forms of construction existing to-day, but only to refer to the appropriate literature. The author will confine himself to such arrangements as are operable with tubes similar to those used for making measurements, or television reception tubes which are available to everybody.

A suggestion for the use of ordinary cathode-ray tubes for scanning positive transparencies or films originated from Thun (summer, 1930). This suggestion became a reality some time later by the work of the author. As it has been retained in principle until to-day, this suggestion with its practical realization will be discussed in this section in more detail. The principle of this transmitter is explained by reference to the experimental device shown in Fig. 436. The deflecting plates of the receiving and transmitting tubes are connected in parallel so that with suitably selected line scanning voltage (voltage at the vertical plates) and picture repetition frequency (voltage of slow frequency at the vertical plates), the rays in both tubes are in synchronism and scan a rectangular surface in successive lines. The resulting picture on the fluorescent screen of the transmitting tube is projected sharply through a powerful condenser lens on the positive transparency to be transmitted. A photo-cell is arranged behind the positive transparency. A certain amount of light corresponding to the position of the fluorescent spot at any moment falls on the photo-cell. The magnitude of the light stream depends on the amount which gets through the transparency at the point of projection of the spot. When tubes such as those described in this book are used with anode voltages which may reach 8 000 volts, voltage variations are produced across the photo-cell which are well above the noise level, i.e. are easily amplified. The amplified

potentials in the diagram discussed are taken to the receiving tube where intensity modulation takes place by means of the brightness control electrode. This simple arrangement enables many interesting experiments to be made with excellent results, using tubes generally employed for measuring purposes at the transmitting end, television tubes on the receiver side, ordinary mains and discharge equipment, and photo-cells with argon filling in conjunction with aperiodic amplifiers (see above). It is particularly well suited for demonstration purposes.

(A) Choice of Scanning Voltages. At the beginning of the development the choice of scanning voltages lay mainly between sine wave and saw-tooth oscillations. Scanning with

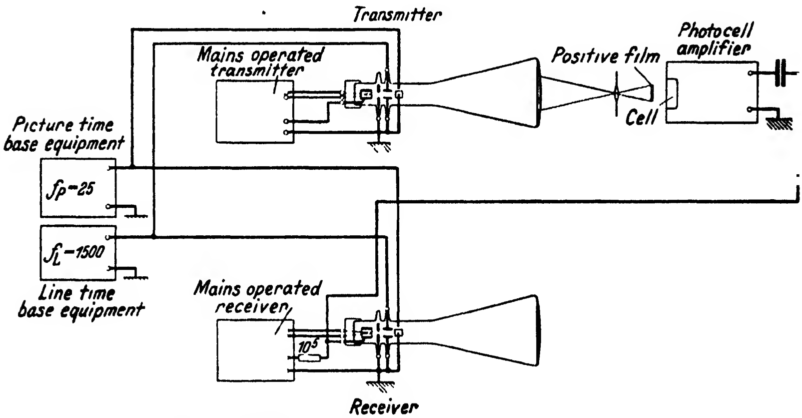

Fig. 436. Compact Circuit for Television Experiments

sinusoidal wave forms has the advantage that extremely low demands are made on receivers and amplifiers, and that the selection of picture and line voltage is particularly simple. The production of the picture and line voltages can be made easily by suitable sources of frequency. Although sinusoidal deflection appears so advantageous it is not used in practice. Considerable variation in brightness takes place with sine wave deflection due to variable ray velocity. The edge of the illuminated surface limited by the point of reversal appears very bright; the centre on the other hand is relatively dark. This can be mitigated by masking the edge of the picture, a measure which is in any case advisable at the receiving end in order to obtain a sharply-defined edge to the picture. A further

disadvantage is the resultant mean picture brightness which is low in comparison with scanning by means of saw-tooth oscillations. The irregular speed of the scanning produces a variation in the amount of detail possible on the picture. The middle of the picture on which, in particular, attention is centred is scanned most rapidly, and therefore produces the worst tracing as long as appreciable time lag influences the choice of line frequency. If serious inertia is present subsequently, which is probably always the case, this will, in the case of sinusoidal scanning, adversely affect the contours of the line much more than scanning in one direction. It is known that inertia causes not only contour diffusion but also a time displacement of the picture elements. This displacement becomes noticeable immediately with the forced synchronization of the experimental arrangement discussed, if the scanning frequency is chosen too high in respect of the inertia of the arrangement. As a rule it is clearly seen before contour diffusion which actually starts simultaneously with it. Displacement due to inherent inertia is not serious in single direction scanning, but with two direction motion, as is the case with sine wave control, disintegration of the picture sets in and compels operation to be made with an unnecessarily low line frequency and correspondingly low number of picture points. The effect of the disintegration has been discussed elsewhere by the aid of examples.(4) In view of the above, scanning should only take place by means of saw-tooth oscillations. All the necessary details about the effective production of these oscillations are to be found above (Chapter II, page 245 *et seq.*). It is of particular importance that the time occupied by the fly-back should be kept as short as possible. Return traverse of the picture scan is particularly serious. It gives rise to streaks of light which run right across the field of the picture, and on the dark portions are particularly annoying in the receiver. Return traverse in the line scan also has its disadvantages in that the picture width, and therefore the possible number of picture points and the possible contrast interval, are also reduced. In order to avoid disturbance due to the fly-back at the actual discharge, various methods can be adopted.

1. By reducing the time constants of the discharge circuit as far as possible, the actual resetting period is kept small and is only a few per cent of the duration of the actual cycle.

2. Line and picture voltages are coupled together so that

the return traverse occurs at a corner or side of the picture. To do this it is necessary to suppress the line traverse for a short period during the fly-back of the picture traverse. (Hudec method.)

3. During the picture return traverse, a local auxiliary circuit, or better still the transmitter, produces an impulse which obscures the ray. (The author's suggestion.)

The following points require consideration in the selection of line and picture frequency. The necessary picture frequency depends on whether the screen or the receiving tube has any after-glow. Very soon after the first practical experiments were made on after-glow screens it became evident that with the usual character of the illumination curve, considerable disturbance occurs even when relatively slow movements occur in the picture. Immediately afterwards, screens with the shortest after-glow were used. As the illumination curve cannot be altered or the luminosity suddenly changed, it is usual to-day to employ fluorescent materials of short after-glow in receiving tubes.(5) To transmit sound films, a picture frequency of 24 per sec. should be selected, since this is just sufficient to avoid flicker. Indeed, if the picture brightness is increased further, it may be necessary to raise the picture frequency to 36 or even 48 per sec. At a given picture frequency, the line frequency should be so adjusted that tracing in the line and picture directions is equally good. The standard of fineness in the picture now usual requires line frequencies of the order of 4 500 to 6 000 cyc. or more.(6) Hudec, and about the same time the author, suggested that the line frequency should not be chosen as a whole multiple of the picture frequency, so that the lines may change slightly in position. Line movement produces a better visual impression.(7) The artifice of line movement can be dispensed with if the size of the fluorescent spot or the magnitude of the discharge voltages used is so adjusted that the lines close up to each other without any considerable intervening space.

It is advisable to have closer contact of the lines on the transmission side also. An unnecessarily large line interval does not produce any considerable decrease in definition, but does lessen the luminous efficiency according to the optical laws of projection. Here, let us refer shortly to the static limits which require consideration both in the use of the receiver and the transmitter.

(B) Static Limits to Picture Definition. The most important limit is set by the number of fluorescent spots which can be aligned without any appreciable overlapping on the luminous surface of the screen. With smaller sizes of bulb the illuminated surface, allowing for the curvature of the screen and its dimensions, is an area of about 10 × 12 cm.; with larger and special bulbs, the glass work of which cannot be considered as material in regular commercial production, the size of the picture is, say, 15–18 × 18–22 cm. The diameter of the fluorescent spot in the usual arrangement is of the order of 0·5 mm. in the small and medium size, and about 1·0 mm. for the largest size, so that there is room for 40 000 or more picture points close together in the field. By slightly altering the design of the electron-optical system of the source of the rays, the point diameter can be reduced still further. But such alteration results in a change of the brightness of the spot. The grain of the screen is the cause of a further static limit which calls for attention at the receiver end. Fig. 437 gives an idea of the extent to which the grain can limit the gradation attainable. This illustration shows that the grain cannot be disregarded as a picture fault, and that the production of very fine-grained fluorescent screens is important for transmitters and receivers.

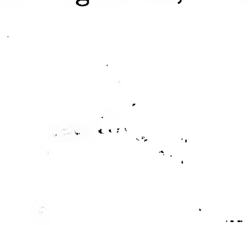

Fig. 437. The Grain of the Fluorescent Screen and the Picture Point

Another static limit which reduces seriously the contrast of the television picture in the usual type of tube is set by the halo disturbance already discussed in detail. Pictures with good contrasts (Fig. 434) cannot be obtained until the halo has been reduced by one of the methods previously discussed (Chapter I, page 141 *et seq.*).

If the static limits permit of the existence of the required number of picture points, and if the deflecting voltages of the time-base are selected in accordance with the above considerations, then the most important conditions for good picture scanning at the transmitter and picture synthesis at the receiver are fulfilled.

(C) An Electron-ray Scanning Transmitter for Film and Its Limitations in Operation. Fig. 438 shows a complete view of a cathode-ray transmitter used in the author's

earlier experiments. In the background is the cathode-ray tube with the mains equipment for several thousand volts. In front of the tube is the device for moving the film. This is more

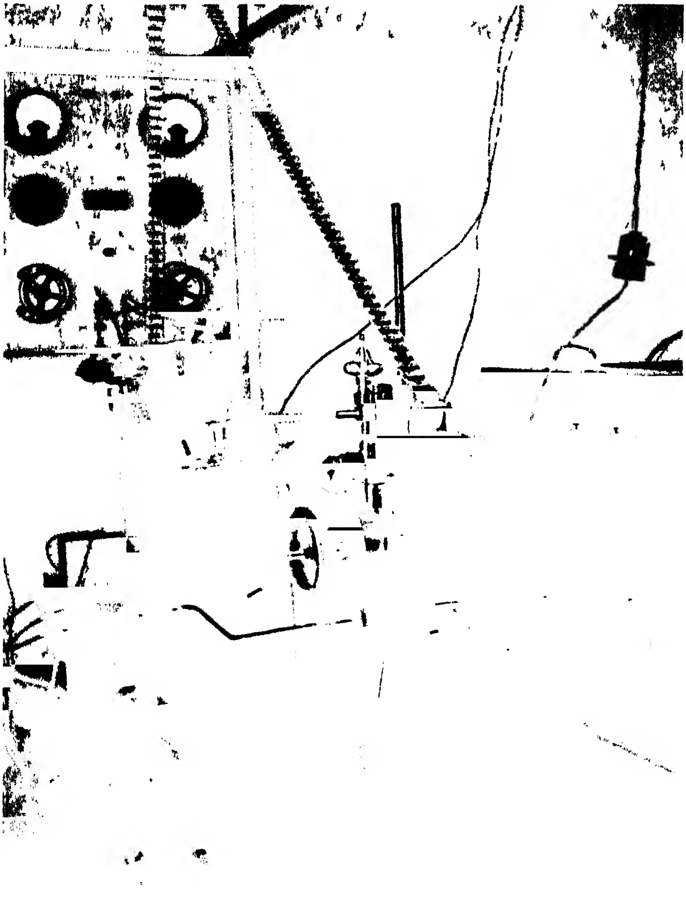

FIG. 438. TRANSMITTER WITH CATHODE-RAY TUBE FOR FILM SCANNING

clearly shown in a later photograph. The box containing the photo-cell and first stage amplifier is arranged in front of the film drive, and at the side of the main amplifier. Details of such amplifiers are to be found above in Chapter II, page

194 *et seq.* Optical errors due to the curvature of the bulb of the tube can be ignored in this case. With very powerful condensers, which must be used for this purpose, the decrease in brightness towards the edge of the picture is very considerable. In television this decrease in brilliancy is very troublesome. Consequently, it becomes necessary to use objectives

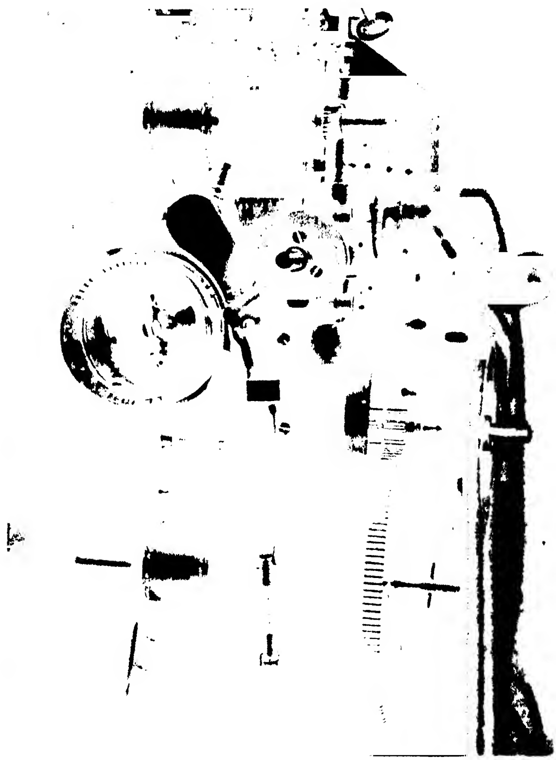

FIG. 439. FILM DRIVE WITH OPTICAL REPRODUCING SYSTEM AND CONTACT FOR PICTURE TIME BASE

of relatively long focal length (7·5 cm. or more) if the whole of the film frame is to be illuminated evenly. The methods of moving the film and the high power optical system of long focal length are clearly shown in Fig. 439. Synchronization between the film drive by the Maltese cross and the time discharges which is necessary in transmission, is carried out very easily in the example shown by picture time base operating

through a mechanical contact, which is coupled directly to the film drive. This contact is introduced into the time base discharge circuit in place of the discharge tube, and operates very rapidly. By connecting a resistance of several hundred ohms in series, it is possible to reduce the impulse somewhat. By using special valves with low microphonic noise in the first stage, disturbing voltages due to the Schröt effect are kept below the signal voltage in spite of noises and heavy vibration.

Two limitations which are very difficult to surmount in the development of cathode-ray scanning transmitters are those set by the amount of light available and the inertia of the transmitting fluorescent screen.

Fig. 440. Line Raster at the Receiver End Modulated by Schröt Voltage

The first limit is set by the condition of the grid circuit in the first stage. If a specified minimum time lag is demanded from the photo-cell and first amplifying stage, then a certain maximum sensitivity will be attainable. But this sensitivity is less the smaller the time constant involved (see Chapter II, page 218 *et seq.*).

If, in the process of scanning, the current due to the light change which occurs falls below this limit, i.e. if the signal voltage falls below the Schröt voltage, then only the impression which is characteristic of the Schröt voltage can be reproduced in the picture in the receiver. Every trace of the true image of the picture then disappears. Fig. 440 represents an old photograph of a line raster at the receiver end, strongly modulated by the Schröt voltage. In order to provide a sufficient degree of contrast, it is necessary for the change in photo-electric current which occurs from light to dark to provide a potential of at least 10^{-5} volts across the grid resistance. It is possible to attain this condition with a time constant of about $\frac{1}{500000}$ sec. by using modern cathode-ray tubes with efficient cathodes under

favourable operating conditions, and by the employment of particularly good photo-cells in a circuit with low capacitance. In order to obtain fine picture scanning at increased picture frequency with the cathode-ray transmitter, it is necessary to use high-vacuum, high-voltage oscillographs. By using high voltages for electron acceleration, the increased brightness which is necessary when working with lower sensitivity photo-cell input circuits, which have lower time lag, is obtained. The question of screen inertia and its measurement has already been discussed previously (Chapter I, page 105 *et seq.*). If the resultant inertia of the photo-cell and amplifier circuits is less than that of the screen it is very simple, with the experimental contrivance shown in Fig. 436, to follow the effect of screen inertia on the televized picture. To do this it is only necessary to oscillograph the alternating output voltage which is produced if a narrow gap perpendicular to the line direction is masked off from the scanned picture. If the line frequency is raised above its normal value, then the effect of inertia will become more apparent; if the line frequency is slowed down considerably, it is possible to recognize the part played by the final spot diameter in limiting the definition.

FIG. 441. OSCILLOGRAM FOR TESTING THE TRACING EFFICIENCY OF A TELEVISION TRANSMITTER

An oscillogram for making apparent the inertia present at a line frequency of about 1 000 cyc., which is characteristic of the possible definition for the older contrivance under examination, is given in Fig. 441. The ordinate gives the value of the voltage supplied by the photo-cell amplifier, and the abscissa the time interval, which at the line frequency mentioned amounts to 0·001 sec. from the beginning to the end of the scan. In order to find out how far the inertia of the screen, the picture point diameter, and other sources of lag in the arrangement are responsible for the lack of sharpness which results, it is advisable, in addition to the measurement indicated, to carry out further investigations with very rapidly rotating mirrors or with devices in which the fluorescent spot

is moved at different high speeds in front of a slit. In the last method mentioned, measurements should be made with a calibrated, and well-screened photo-cell circuit to ascertain what variations occur with change of frequency. Fig. 442 shows a special slit arrangement produced for this purpose; slits of varying width can be brought up in front of the fluorescent stroke. By masking the centre portion, a doubling of the frequency can be obtained, and this is desirable in order to avoid disturbances.

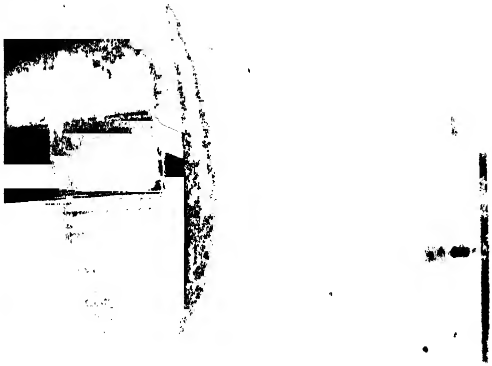

FIG. 442. INTERMITTENT ILLUMINATION FOR MEASURING AFTER-GLOW BY ARRANGING A SLIT IN FRONT OF THE PATH OF THE SPOT DEFLECTED BY H.F. IMPULSES

The method of investigation is simpler than the previously mentioned one using modulation of the ray intensity, as it is easier to control and correct frequency errors. For instance, correction is made always by adjusting the screen deflection to the same value. Investigations by this method confirm the results already given, that a calcium tungstate screen has a time lag of about $\frac{1}{1000000}$ sec., and with modern screens the value is less than $\frac{1}{5000000}$ sec.

In the more modern forms, the film transmitter mentioned permits of the scanning of pictures of very fine grain. The reason why the cathode-ray transmitter has been treated at some length in this section, is that the mechanical devices common to-day in transmitters do not, by any means, allow the line and picture scanning frequency or the method of scanning

to be changed as quickly as the cathode-ray transmitter. Mechanical transmitting devices for scanning with velocity modulation are quite useless.

4. **The Cathode-Ray Television Receiver.** The use of the cathode-ray tube for television reception presents four main complex problems.

1. The production of sufficiently small well-defined fluorescent spots.
2. The attainment of the maximum possible brightness in the resulting screen spot, and therefore in the picture scanning.
3. Accurate control of the brightness.
4. Accurate control of the position of the spot in synchronism with the transmitter scanning.

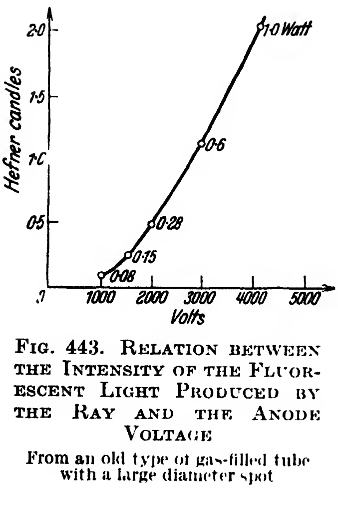

FIG. 443. RELATION BETWEEN THE INTENSITY OF THE FLUORESCENT LIGHT PRODUCED BY THE RAY AND THE ANODE VOLTAGE

From an old type of gas-filled tube with a large diameter spot

The first and third of these problems have been fully discussed in various parts of this book. There is, also, especially in the sections dealing with cathode and fluorescent screens, detailed information concerning the second problem. Nevertheless, in view of the importance of the combinations for the suitability of the cathode-ray tube for television we will, at this point, make a few observations, some of which will be illustrated by examples.

(A) THE BRIGHTNESS ATTAINABLE. Measurements made with an old gas-filled tube with a rather large spot diameter and particularly high ray current, of the relation between total light intensity of the fluorescent illumination, the anode voltage and effective ray output, are given in Fig. 443. In this case, the energy of the ray was distributed over a surface of about 25 cm.[2] The way in which the efficiency of the screen in this range varies with the voltage is clearly shown, and is an important reason for not working with too low an anode voltage.

The existence of luminous screen saturation as a consequence of the limited number of centres of excitation, means that the light density does not decrease proportionally to the increase

in the area of the scanned surface.[8] On the contrary, the brightness, starting with the values measured from the smaller surfaces, decreases more slowly than would be expected from the arithmetical law of decrease in brightness. This fact is favourable to the attainment of larger and brighter pictures, but unfavourable to the creation of smaller pictures in tubes for projection purposes. Further details of the question of screen saturation are to be found in Chapter I, page 127 *et seq.* By means of the brightness characteristic, an estimate can be made of its value in lux for each position of the operating point on the scanned surface, and the size of each picture.[6]

By reversing a well-known equation, it follows that

$$\text{Intensity of illumination in lux} = \frac{\text{candle-power (Hefner) (spot brightness)} \cdot 10^4 \cdot n}{\text{cm.}^2\ \text{(picture surface)} \times 0{\cdot}8}$$

For example, from the characteristic (No. I, Fig. 51) of a modern receiving tube and the above equation, we get for a scanned surface area 18 × 22 cm., a value of above 45 lux, and for a picture area of 13 × 16 cm. a corresponding lux value of 80. The brilliancies are of the same order of illumination as those existing in average cinemas. They are, however, somewhat high for picture frequencies of 25 usual in television to-day. According to the relative observations made by the author, the flicker limit at these picture frequencies is reached at 5 to 10 lux. Even when the picture frequencies are increased to 30 or 35, the brightness of the scanned surface may not be increased beyond 20 lux, and even smaller lux values have been recorded for the flicker limit.[9]

With intensity control, however, the mean light intensity drops to about one-fifth in comparison with the intensities given in the measurements, if sufficient contrast is to be obtained. With velocity modulation, the mean light intensity is about equal to that obtained from measurement, since in this case the whole of the ray energy is used for exciting fluorescence. With velocity modulation particularly, the luminous intensity of small screen pictures is sufficient to project enlarged images, in spite of absorption and aperture losses, without the brilliancy of the reproduction being reduced too much. Fig. 444 illustrates this in the form of an earlier projected screen picture. The efficiency of this method of

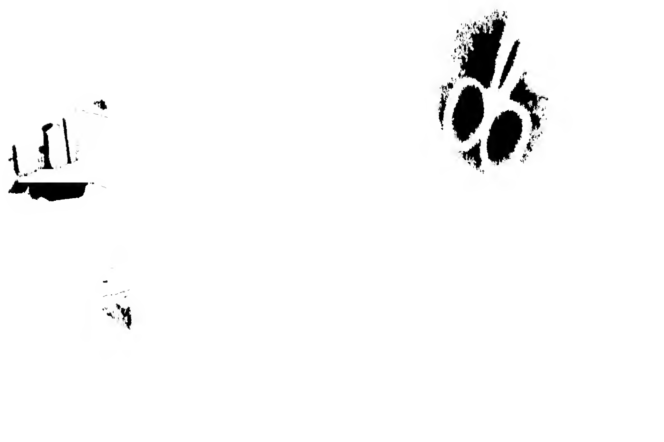

FIG. 444 PICTURE FROM AN OLD TYPE OF PROJECTION RECEIVER IN OPERATION (Von Ardenne Feb 1931)

(a)

(b)

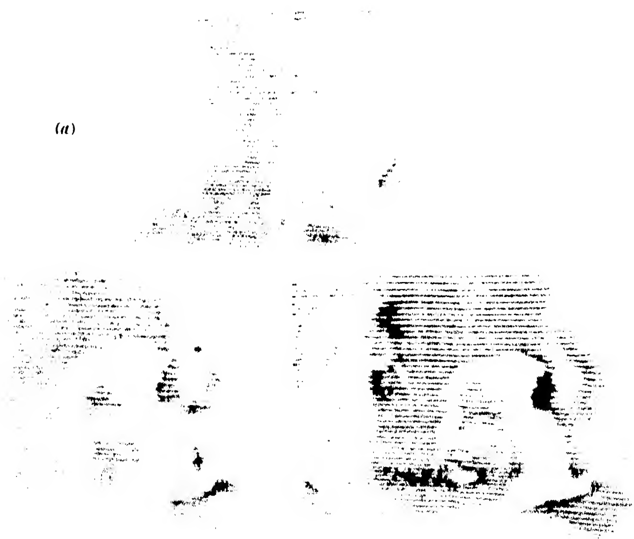

FIG 445 TELEVIZED PICTURE FROM AN OLD TYPE OF GAS-FILLED TUBE
(a) Normally modulated, (b) and (c) over-modulated

brightness control can best be ascertained from the sharpness of the lines forming the boundary between black and white portions of the picture. Figs. 445 and 446 illustrate the way in which errors in brightness control become noticeable. The human eye is very sensitive to this type of distortion in the body of the picture.

With modern high-vacuum tubes, the brightness control errors illustrated (Fig. 446) can be ignored. The construction of special tubes for television differs from that in the case of tubes designed primarily for making measurements, by the

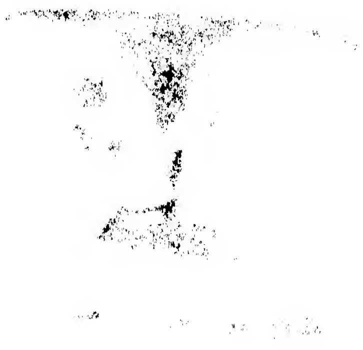

FIG. 446. TELEVIZED PICTURE DISTORTED BY FAULTS IN THE ILLUMINATION AND DEFLECTION CONTROLS

fact that larger pictures are required, particularly large bulbs and fluorescent screens are used, or else the screen and bulb design must be suitable for projection. If finer scanning is adopted, then it is necessary to select a definite size for the picture if the full effect of the greater detail of the finer scanning is to be appreciated, bearing in mind that the minimum distance of distinct vision for the eye is 25 cm.[10]

The synchronization of the ray motion between the transmitter and the receiver is of particular importance.

(B) CONSIDERATIONS IN THE CONSTRUCTION OF A RECEIVER WITH SPECIAL REFERENCE TO THE SYNCHRONIZATION OF THE MOVEMENT OF THE RAY. The simplest form of synchronization consists in the parallel connexion of the deflecting plates on the transmitter and the receiver end. This parallel connexion is

also possible in principle for wireless transmission. For intensity modulation three channels would be necessary. The advantage of parallel connexion is that the receiver remains synchronized in spite of any variations at the transmitter. For wireless transmission the method of forced discharge has been established.

All the necessary information about the production of electrical synchronization has already been given previously (Chapter II, page 250 *et seq.*). In order to avoid picture distortion, the saw-tooth voltages must have a good wave form when used for television purposes. In addition, constancy of the discharge circuit is necessary over long periods in order that synchronization of both discharge voltages may not be upset. Fundamentally, the conditions appear more complicated than with mechanical scanning in view of the double synchronization of picture and line voltage. In practice, however, they are simpler, because the power required is smaller, necessitating a lower output stage, and the time constants of the circuits involved are small.

FIG. 447. COMMUTATOR FOR PRODUCING MECHANICALLY A SYNCHRONIZED LINE FREQUENCY

As the constancy of the usual local supply is not sufficient to synchronize the picture and line discharge voltages of the transmitter over long periods, it is necessary to make the transmitter force the receiver into synchronism. In practice, it has become usual, in accordance with Hudec's process, to superimpose a short impulse at the end of each line, and a corresponding impulse at the end of each picture on the video frequency signal at the transmitter end, these signals being of comparatively large amplitude. The formation of synchronizing impulses can be made with the assistance of very accurately constructed contacts which are placed on the axis of the scanning disc or mirror wheel. Fig. 447 shows such a special contact arrangement which was made for experimental purposes. In modern practice the controlling impulse is usually created by punching an additional circle of holes next to the actual scanning apertures in the Nipkow disc. One

of the synchronizing slots which are spaced round the circumference of the disc is widened and provides the picture change impulse. A typical disc for the formation of short synchronizing impulses at the end of each line and a long impulse at the end of each picture is shown in Fig. 448. In front of the series of slots, a special projection system is arranged and this provides the synchronizing impulse through a second photocell and an amplifier of lower sensitivity. Details of this system are to be found in a publication by Hudec and Perchermeier.(11)

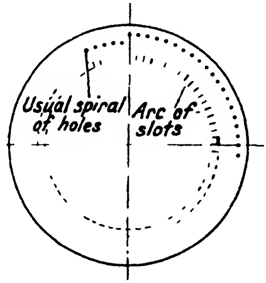

FIG. 448. NIPKOW DISC (HUDEC) FOR PRODUCING A SHORT SYNCHRONIZING IMPULSE AT THE END OF EACH LINE AND A LONG ONE ON THE COMPLETION OF EACH PICTURE

The suitability of the wave-band of 5–8 m. for the transmission of wide frequency bands which was forecast for television transmission some years ago by W. Hahnemann,* on the basis of practical observations, and later more nearly established after F. Schröter(12) had carried out measurements in this connexion, has been confirmed entirely in practice. Furthermore, it has been proved that only such circuits for picture reproduction as make the latter faithful in phase and amplitude down to the lowest frequencies, and also transmit the d.c. value corresponding to the mean picture brightness, are worthy of consideration. The modern picture receiver almost always contains an intermediate frequency circuit with a very efficient aperiodic intermediate frequency amplifier without amplification in l.f. stages.(13) The brightness control voltages are taken direct from the intermediate frequency detector so that the d.c. value is thus obtained. A certain clarification in respect of the most effective method of forming synchronizing impulses for picture and line time bases seems to have been reached through the definite experience obtained from the Berlin experiments with the Schriever process.(14) The construction of the intermediate frequency receiver for the required band width is purely a h.f. problem, a discussion of which would be beyond the scope of this book.(15)

The high frequency applied to the last stage of the

* *Vide* (*inter alia*) Fr. Pat. No. 682924. Gr. priority 20th October, 1928, and 27th March, 1929.

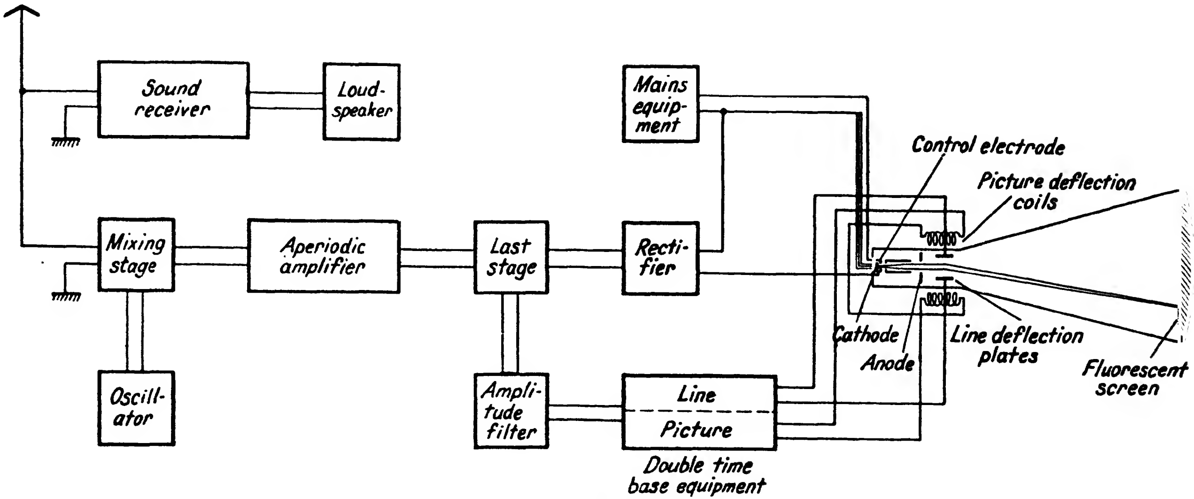

FIG. 449. DIAGRAM OF A COMPLETE TELEVISION RECEIVER

intermediate frequency section as shown by the diagram of a television set given in Fig. 449, reaches the receiver detector as well as an amplitude filter which will be discussed in more detail later. As already stated above, the simultaneous use of the d.c. components is a condition of distortionless reproduction. It is most easily carried out by coupling electrically the receiver detector and the brightness control electrode of the cathode-ray tube. The easiest way is to rectify in the cathode-ray tube itself. This type of rectification, however, has the disadvantage that the ray current of the cathode-ray tube can only be used for a fraction of the time, so that relatively dark pictures result. Proof of this statement is provided by the diagrammatic illustration, Fig. 450. Actually, the conditions are rather less favourable than the illustration indicates in consequence of the displacement of the operating point into the range of less negative grid voltages due to the synchronization static value. If the intermediate frequency voltage supplied to the last stage is suited to the cathode-ray tube, i.e. if the peak value of the intermediate frequency reaches the grid voltage value, when the tube current is as great as is consistent with good definition, the average picture brightness from rectification in the cathode-ray tube is only one-third of that possible by other methods of operation. As a reserve of brightness is essential, rectification in the cathode-ray tube is not recommended for practical application. Considerably better conditions exist, as can be seen immediately, if rectification is not carried out in the cathode-ray tube itself as a half-wave rectifier, but in a separate rectifier preceding the cathode-ray tube. With full-wave rectification, even at relatively low intermediate frequencies, about 60–80 per cent of the maximum ray current is usefully employed, according to the extent to which the fluctuations due to the intermediate frequency are smoothed out by parallel capacitances. It is possible at intermediate frequencies of 6 mc. to use the cathode-ray tube even with half-wave rectification almost as well, as is shown diagrammatically in the drawing, Fig. 450, for full-wave rectification. When such high intermediate frequencies are employed, it is necessary to use band-pass filters as coupling devices. The proof that the wide frequency bands can be transmitted perfectly in this way is given in an American work.* Fig. 451 illustrates a practical example of a simple rectifier circuit. A

* See Reference [40] at end of Chapter I.

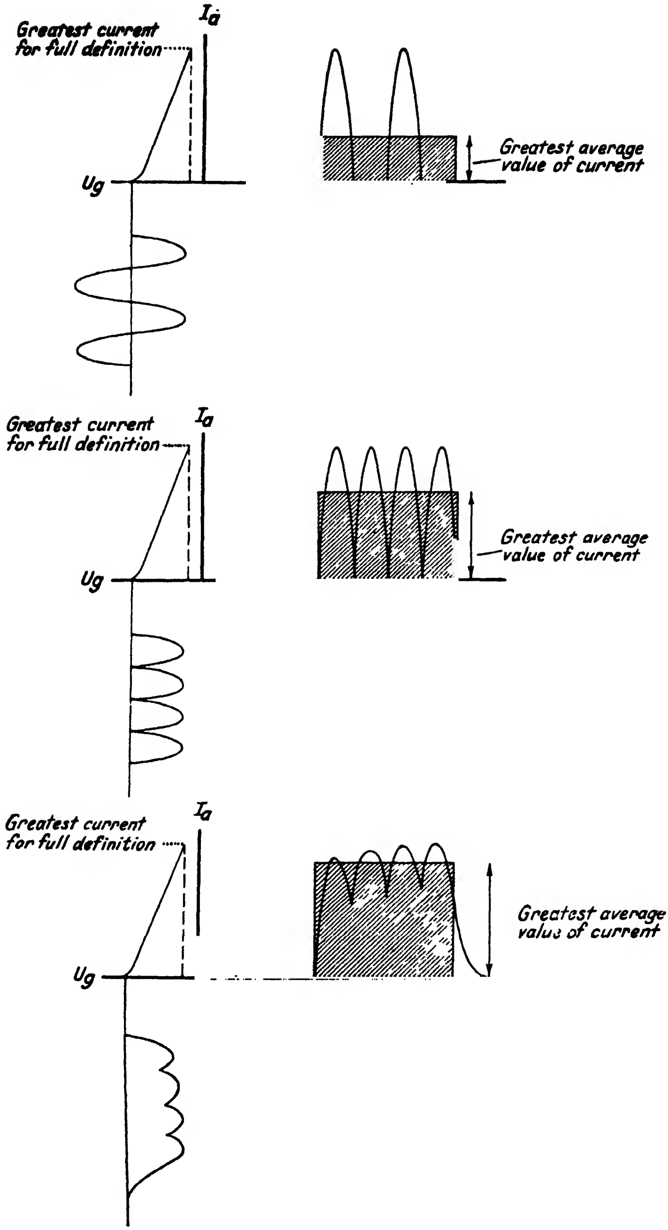

FIG. 450. RELATION BETWEEN THE METHOD OF INTERMEDIATE FREQUENCY RECTIFICATION AND THE MAXIMUM RAY CURRENT OF THE CATHODE-RAY TUBE

limit to the smoothing out of the fluctuations by the capacitance on the output side of the rectifier is naturally set by the decrease in sharpness of the picture due to the discharge time. It is advisable, therefore, only to use this with great care. A proper compromise can be made easily by suitable choice of the resistance *R* in Fig. 451. If the assembly and the conductors are low in capacitance, the resistance can be brought up to values of the order of 10^4 ohms without the sharpness of the

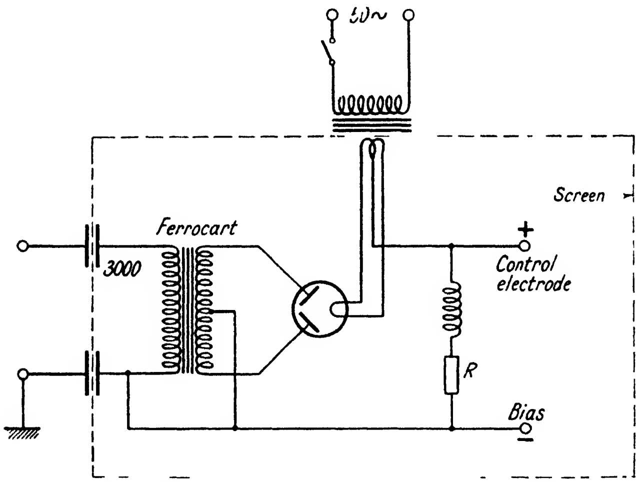

FIG. 451. FULL-WAVE RECTIFIER FOR LONG WAVE INTERMEDIATE FREQUENCY

picture being noticeably affected. With an ohmic resistance of this magnitude, voltage changes of 10–20 volts are necessary for the light-dark control of the cathode-ray tube, and can be obtained with relatively low amplifier output, so that the last stage need be scarcely designed for greater power than the other stages of the intermediate-frequency amplifier. Also, when full-wave rectification is used, intermediate frequencies up to about 1·5 mc. still remain clearly visible in the television raster. The intermediate frequency gives the picture the appearance of a printed illustration. According to the proposals of Schriever mentioned above, the Berlin transmitter is controlled in the following way. The normal aerial current is adjusted to values between 25 per cent and 30 per cent to correspond to the darkest tone value of the picture. The

degree of modulation is brought about by control in the upward direction from the figure mentioned to the most brilliant illumination and maximum current. The synchronizing signals, on the other hand, are transmitted by complete interruption of the aerial current after each line is finished and after the completion of each picture. The period of time taken up by the synchronizing holes amounts now to about 5–7 per cent of the scanning time for one line or one picture, so that there is a great difference in the frequency components of both impulses which permits of the use of frequency operated devices for separating the line and picture signals. This method of modulation, which has been thoroughly tested in practice, has the

FIG. 452. OSCILLOGRAM OF THE HIGH-FREQUENCY WAVE OF THE BERLIN TELEVISION TRANSMITTER WITH SYNCHRONIZATION SPACE DURING THE PICTURE INTERVAL

advantage that only a small fraction of the output of the transmitter—about one-tenth of the actual time—is tapped off for synchronization, i.e. lost in the transmission of the body of the picture. Furthermore, the cathode ray is obscured at the end of each line and at the end of each picture, so that the extremely annoying return sweeps are not seen. Fig. 452 shows an oscillogram of an intermediate-frequency voltage received from the Berlin transmitter with dark control, an example of present-day practice. One of the chief difficulties of picture reception by radio is that of obtaining constant synchronizing impulses, i.e. impulses whose amplitude is not affected by the momentary value of the video signal, nor impaired by the mean noise level at the output of the receiver. Very slight fluctuations, especially in the magnitude of the peak of the synchronizing impulse, are in themselves sufficient to cause considerable line displacement or changes in the height of the picture. A dull picture lacking contrast, and an unpleasant wavering, are produced. Such changes are more effective in producing these effects the greater the possible

range of adjustment of the signal over which locking occurs. The problem of creating regular synchronizing impulses from the voltage mixture at the intermediate-frequency output was solved by connecting up an intermediate valve stage the typical characteristic of which is shown in Fig. 453. Here the operating point is displaced far into the region of high negative bias (for instance, in Fig. 453 to – 5 volts) so that voltage disturbances which exist in the pauses of transmission

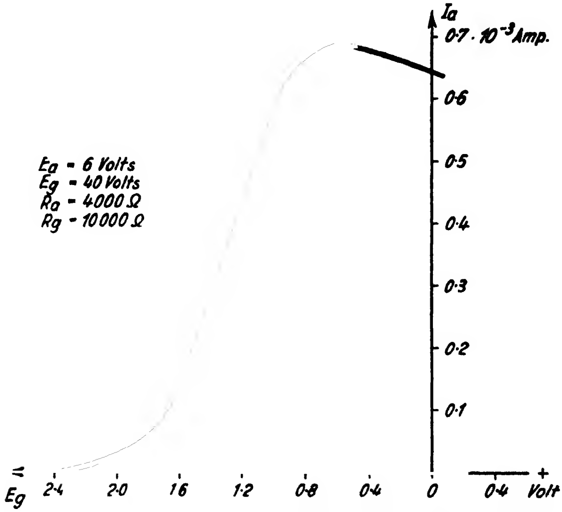

FIG. 453. CHARACTERISTIC OF THE AMPLITUDE FILTER WITH A SCREEN GRID VALVE

never reach the figure where the anode current of this amplitude filter commences to flow. Immediately after the synchronizing interval a current, the mean value of which is about half the maximum value which can be read off the valve characteristic, flows in the anode circuit subject to correct division of the receiver output voltage. This current is entirely independent of the momentary value of the modulation of the transmitter (i.e. independent of the picture brightness), because the characteristic falls again after reaching its highest point. Even with a characteristic such as that of Fig. 454 which is only obtained with difficulty using single grid valves, the mean value is not sufficiently independent of all amplitudes which may be present—bearing in mind the ever-increasing

grid current—for the synchronizing signals to be completely separated from the picture signals. The fall of the characteristic after passing the peak is, in the case of the screen grid valve (the characteristic of which is indicated in Fig. 453), attained by the familiar current distribution effect. (Arrangement of retarding field.)

Suitable choice of auxiliary grid voltage easily enables the drop to be brought to a value where operation is practically independent of the momentary degree of light modulation at the transmitter.

The process described is intended finally to cut out and

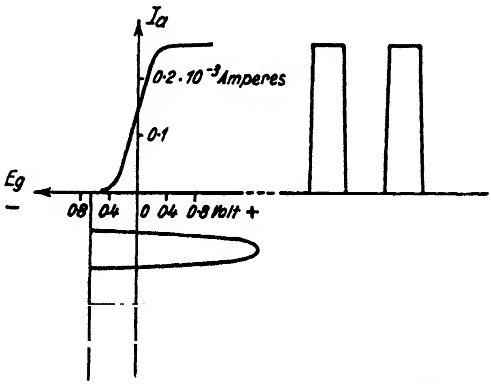

FIG. 454. METHOD OF OPERATION OF A NORMAL AMPLITUDE FILTER

utilize a narrow band from the whole modulation interval of the transmitter; for example, an interval of 20–25 per cent in order to produce the same current. The regularity of the synchronizing impulse obtained, which was also controlled oscillographically, is so good that even without the addition of frequency filters after it, it gives extremely stable synchronization with normal thyratron or valve time circuits. The pictures remain stable and free from distortion for several hours. The brightness was sufficient to make photographs of the receiver screen pictures with exposures of a fraction of a second, so that a sharp image of the picture could be obtained in spite of the continuous movement in the transmitted sound films. Three typical untouched cut-outs are shown in Fig. 455. Fig. 456 gives evidence of the low disturbance level in the synchronization. This photograph was taken during a

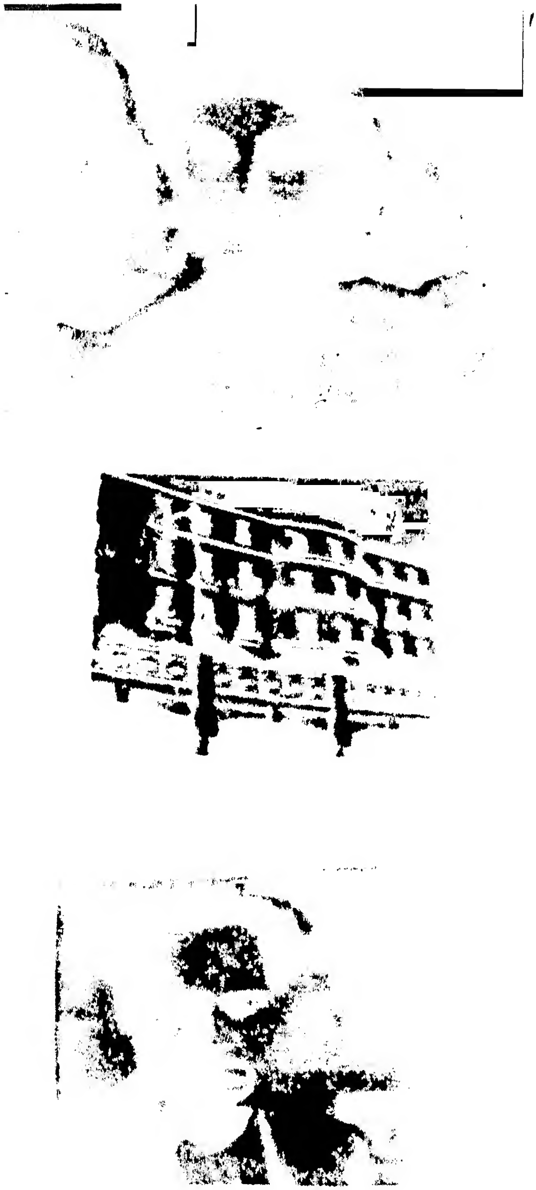

Fig. 455. Unretouched Instantaneous Pictures from a Sound Film Received from a Distant Transmitter
(180 lines, Berlin Station, 1935)

disturbance which was artificially produced, the voltage peaks amounting to 50 per cent of the voltage obtained from the dark value of the transmitter. In spite of these unfavourable conditions, good synchronization was maintained. The disturbance in the picture caused by slight alteration in the length of the line is found indirectly to be not greater than the disturbance due to variation to the illumination control. Conditions are such, therefore, that the possibility of synchronization disturbance is not greater than the disturbance due

FIG 456 A RECEIVED PICTURE DISTORTED BY INTENSE ARCING
(E.g. from a commutator or other current collector)
Showing that the effect of the disturbance is small if the amplitude filter is functioning correctly

to unavoidable causes in the brightness control circuit. Synchronization along a separate channel would not therefore lead to any great improvement in the picture.

5. **The Operation and Possibilities of Velocity Modulation.**[16] When R. Thun [17] in the middle of 1930 discussed all the fundamental possibilities for the raster process in a comprehensive work, allusion was made to the reversal of the usual method of picture synthesis operating with uniform scanning velocity, i.e. for carrying out picture transmission with a constant ray intensity but variable scanning velocity. This possibility described by Thun himself as *velocity modulation* was not, it is true, practically established. Nevertheless, we will discuss below in more detail the way in which this interesting process can be carried out, because in future, it will be of value for special problems. Velocity modulation necessitates sudden

and considerable changes in scanning speed. For example, it may be necessary, in the definition of sharply-focused contrasts, the edges of which show a brightness ratio of 1 : 10 for the velocity of the ray in the interval of $\frac{1}{1000000}$ sec., to increase from 100 to 1 000 m. per sec. In this instance it is assumed that the contrast sharpness in the length of one line of about 10 cm. corresponds to a picture division of about 10 000 points. Such high velocities, and particularly the extraordinarily high accelerations they involve, can be scarcely attained by mechanical arrangements. Even if the control of the ray is carried out by revolving mirrors as in an oscillograph, the accelerations involved are of such a magnitude that they are a great drawback to any operation involving elements of appreciable mass. Velocity modulation is therefore open to the errors which are inseparable from mechanically-operated parts on the transmission side, and at the reception end, particularly in the synthesis of pictures which are rich in detail. Cathode-ray tubes which have no changes in ray intensity, and are therefore suitable for the Thun method, have been available from the start as devices suitable for velocity modulation in receivers, being free of inertia, particularly simple in construction, and easy of operation. In discussions on velocity modulation, therefore, special attention has always been given to the cathode-ray tube. The particular advantage of velocity modulation lies in a much higher mean picture brightness, to which reference has already been made.

(A) The First Simple Experimental Transmitter for Velocity Modulation. The first problem to be solved in the construction of a transmitter for velocity modulation consists in relating the scanning velocity along the line to the degree of brightness on the picture line to be transmitted. A solution of the problem is most nearly secured by the introduction of an optical inter-coupling. If, for instance, a cathode-ray tube transmitter is used, there is an inter-coupling if the voltages which appear at the output of the photo-electric amplifier are employed to modulate the discharge voltage of the line-time base. Modulation free of distortion can be carried out in this way by a circuit using a screen grid or similar arrangement in the time-base circuit, as discussed in the section on time deflection, where modulation of charging current is carried out by means of a specially designed space-charge grid valve. The principle of velocity modulation is that the

scanning period is greater or less according to the brightness over the line.

The simplest way of effecting equidistant positions of the lines consists in using the same voltage from the photo-electric amplifier which carries out line modulation in order to modulate a second saw-tooth voltage of lower frequency, and use this for line distribution, i.e. as picture voltage. This modulation is carried out without phase change by the introduction of a time base circuit for the picture deflection which is similar in design except for the charging condenser.

FIG. 457. OSCILLOGRAM OF A MODULATED TIME DISCHARGE

If modulation is not provided for the picture time-base circuit, then the lines will be more or less close together according to their mean brightness. In the dark portions which are scanned quickly they will be close together, and vice versa. The variations in mean brightness and in images with completely covered and uncovered lines, the contrast ratio can be read off directly from the differences in distance. Compression of the dark lines and separation of the light ones tends against a natural distribution of brightness. Experiments with a large number of the pictures of the most varied structure showed that on an average the character of the picture suffered too much when the lines were not equalized. By modulating the voltage of the discharge circuit of the time base of the picture frequency, the slope of the curve at the instants of dark lines becomes considerable, and vice versa. If modulation is carried out with the correct amplitude—if both discharge circuits are not equally sensitive through the employment of valves which have not exactly the same sensitivity, a simple voltage divider will enable the necessary adjustment for equality to be made—the lines will be separated by equal distances independent of their traverse time. Fig. 457 illustrates a cathode-ray oscillogram of a modulated saw-tooth voltage for regulation of the line distance. The oscillogram shows the typical step-like character of a saw-tooth oscillation modulated

for the purpose of velocity modulation. If the line and picture deflecting voltages are modulated free of distortion, and with the correct amplitude corresponding to the picture structure, the scanned picture will appear direct on the screen of the transmitter. The photograph, Fig. 458, shows a velocity modulation transmitter in operation with the picture which can be recognized on the screen. The quality of the picture at the time of operation corresponded to a raster of approximately 5 000

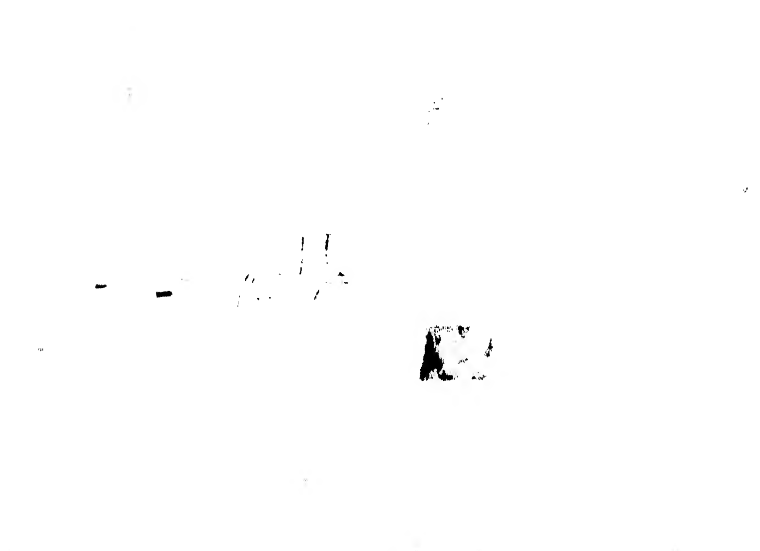

FIG. 458. PORTION OF AN OLD TYPE OF VELOCITY MODULATION TRANSMITTER IN OPERATION WITH PICTURE ON THE SCREEN

(*von Ardenne*, 1931)

points. A positive or negative appears on the transmitter screen according to the phase of the photo-electric amplifier output, i.e. according to the number of stages in this amplifier.

When a diapositive is scanned, the time occupied in scanning naturally remains constant. Also in film scanning, i.e. in the transmission of pictures with fluctuating mean brightness, the time for picture scanning can be forced to be constant by cutting off from the amplifier circuits all frequencies less than the intended number of pictures per second. This, however, means that all the images, even if they have optically different

values of mean brightness, will be reproduced with the same mean brightness. The particular circuit of a transmitter for velocity modulation is illustrated in Fig. 459. This contains all technical details and design for the picture and line modulating equipment. The outstanding characteristic of a transmitter based on the principle of velocity modulation, is that the picture transmitted is visible on its screen. Excellent control is provided by observation of the transmitted picture.

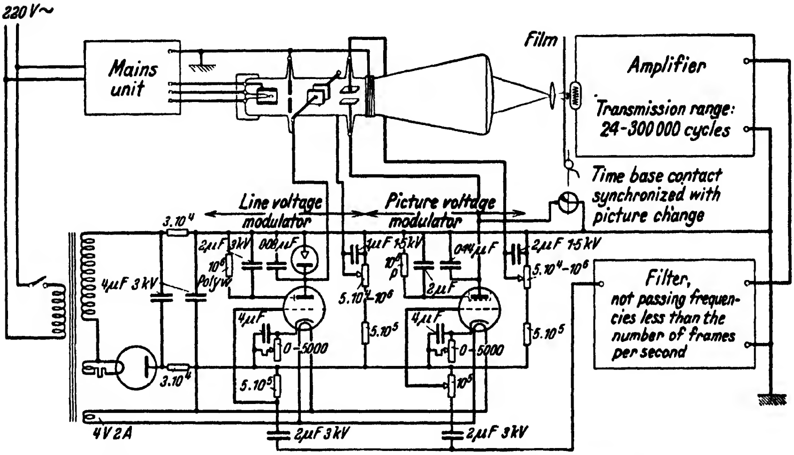

FIG. 459. CIRCUIT OF AN OLD TYPE OF CINEMA TRANSMITTER USING VELOCITY MODULATION

The problem of receiving a picture by the velocity modulation method in the form hitherto described involves connecting the two plates of the receiver in parallel with the two plates of the transmitter.

(B) A SYSTEM OF TRANSMISSION USING BOTH VELOCITY AND INTENSITY MODULATION. In general, pictures taken using the principle of simple velocity modulation have one fault; they lack contrast and their effect is therefore indistinct and lifeless. Omitting other disturbing influences, the contrast ratio of a velocity modulated picture, as is well known, is the ratio of the highest to the lowest deflection velocities over the picture surface. The limited range of modulation of the amplifying valves precludes a higher velocity ratio. A ratio of 30 : 1 should be aimed at in order to secure contrasts such as those usual in photography. If the modulation is limited to the

linear range of the valves, then a contrast ratio of greater than 1 : 5 cannot be secured. A greater ratio is possible, for example, by using variable-mu valves in the discharge circuits which can be modulated. In such a case it becomes necessary to reproduce exactly at the receiving end, the modulation characteristics of the transmitter. If the modulating portion of the transmitter and receiver are not matched—and it is hardly possible to match them exactly in practice—serious distortion of the picture will result. The familiar property of velocity modulated pictures, of showing better definition in the lighter portions than in the darker ones, can be looked upon as an advantage only for low degrees of modulation. Immediately a high contrast ratio is involved, the lack of detail in the darker parts becomes very noticeable. The considerations mentioned are all against the employment of high velocity ratios (greater than about 1 : 5). Nevertheless, in order to obtain a high contrast ratio in the picture, Bedford and Puckle [18] use velocity control simultaneously with intensity control. By superposing both types of control a successful method of securing a high contrast ratio is obtained. By adopting a simple design, Bedford and Puckle were successful in so arranging the modulation ratio that the intensity of the ray is really only decreased in the dark portions. The method of varying the contrast is therefore effective in reducing the intensity of the ray and of the brightness only in the parts where, in any case, little ray energy is available. The main advantage of velocity modulation—supplying very brilliant pictures through operation with the greatest possible ray energy—is therefore retained in practice. Details of the system of transmission developed by Bedford and Puckle are given below, since many of the devices employed can be used in circuits for making measurements.

The main features of the transmitter are to a great extent similar to those of the cathode-ray transmitter designed by the author (Fig. 459). The line raster produced on the screen of a cathode-ray tube is projected by a high power condenser on to the film to be transmitted. Behind the film is a photo-cell with its associated amplifier. Modulation of the discharges of the time circuit is carried out with the help of a screen grid valve (V_1) as shown in the diagram of the time circuit in Fig. 460. Discharge takes place in the line direction through an arrangement of high-vacuum valves (V_2 and V_3).

This arrangement is recommended in the case of the line time-base in preference to one using gas-discharge tubes, since the time lag of the latter leads to disturbances at the end of the line at the high frequencies and varied scanning velocities which must, of necessity, be involved in modern equipment. The formation of the voltage of the picture time-base discharge circuit, which controls the separation distance of the lines, is not carried out by simultaneous modulation of an independent saw-tooth generator but, according to an earlier and similar suggestion of Thun, by "ratcheting" by making use of the discharge in the line circuit at the end of each line. The problem in this case is solved in a very simple way by using the discharge of the line condenser with the assistance of a further valve* (V_4) to effect a short deblocking of the negatively biased grid of a screen-grid valve V_7. In this way a constant current flows to the picture capacitance at the end of each line. The resulting voltage change on the condenser brings about the necessary displacement of the beginning of the following lines. At the time that the picture condenser has almost reached the voltage which corresponds to the height of the picture, a thyratron connected in parallel with it is about to strike. The thyratron receives grid bias through the drop in voltage across the resistance R_8 in the anode circuit of valve V_7. As this anode current consists only of impulses, the bridging condenser C_8 is provided to maintain the bias of the thyratron between the impulses. The effect produced by the picture synchronization process depends on the time constant C_8R_8, the values of which are chosen to be large enough to provide a balance over the longest line present. Every lengthly interruption forced on the line-scanning arrangement leads to a striking of the thyratron V_8. Such a delay is effected every $\frac{1}{25}$ sec. by the aid of the timing device through the picture discharge voltage (Fig. 460). The timing device consists of a thyratron V_{10} and a simple non-linear saw-tooth discharge circuit. The timing device is designed first of all to operate at about 25 cyc. Exact synchronization occurs from the 50 cyc. mains by the aid of the potentiometer shown which bridges the a.c. heating circuit. Valve V_5, shown in Fig. 460 as a voltage limiter, is in parallel with the discharge valve V_2 of the line discharge

* A further valve is provided, because the anode voltage rise at the valve V_3 is limited by commencement of grid current from the valve V_2.

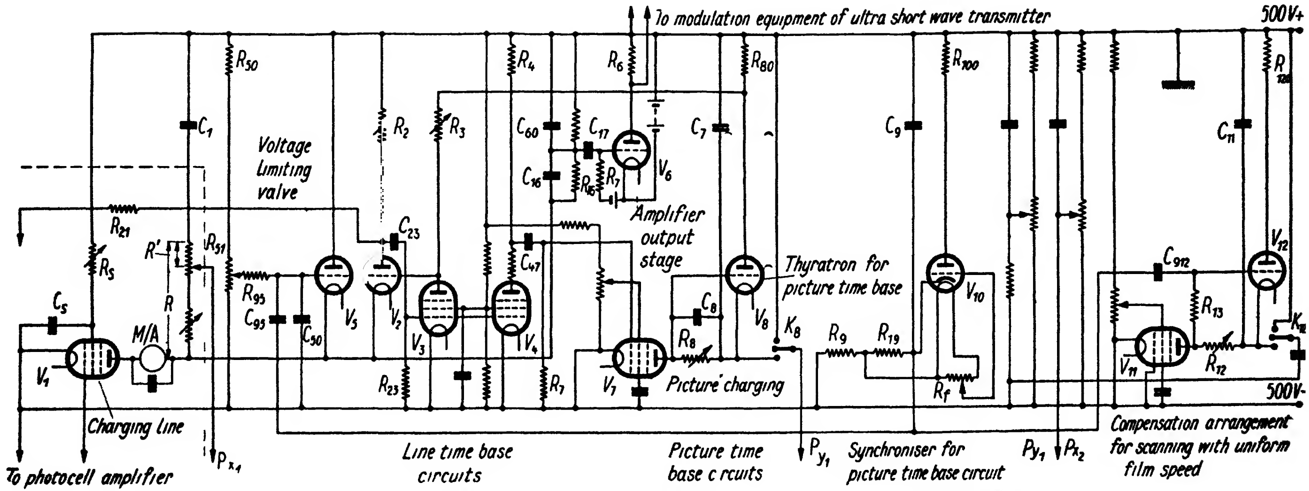

FIG. 460. DIAGRAM OF THE TIME BASE CIRCUITS OF THE FILM TRANSMITTER

circuit. The grid of this valve is adjusted by the potentiometer R_5, to a slightly lower potential than the grid of valve V_2. No anode current, therefore, flows in the voltage limiting valve as long as the normal line time circuit is in action. The impulses of the timing device are impressed on the grid of the voltage limiting valve and ensure that every $\frac{1}{25}$ sec. the grid of V_5 for a short time becomes more positive than the grid of V_2. At this instant the line scanning is discontinued. After the timing impulse, the grid voltage of V_5 drops back again to the original and highly negative value. The rapidity of the return traverse depends on the time constant $C_{50}R_{95}$, which is designed so that a sufficiently long interruption interval occurs. The interval which covers two or three lines is sufficient to allow the thyratron of the picture time-base to strike safely in the way described above. The method of originating the picture deflection voltage, which at first appears unnecessarily involved, has the great advantage that the synchronizing impulses can in this way be transmitted to the receiver as interruptions. The portion of the time circuit of the transmitter so far described comprises those components which are essential for the transmission of diapositives. In sound-film transmissions it is desirable, of course, to work with a film which moves at a uniform rate, particularly in view of the fact that there is a 25 per cent loss of the scanning time with intermittent motion. In order to make this possible, the first thing to do would be to employ the usual process which consists of scanning one line of the continuously moving film. This cannot, however, be used in cathode-ray transmitters, as the author showed in earlier works, because with the higher ray energies necessary, fatigue and saturation phenomena which lead to reduced efficiency in illumination are unavoidable. Furthermore, it cannot be employed in a simple way with the velocity modulation process, on account of the variable time occupied in scanning a line. An interesting way out of these difficulties is provided by another time-base circuit shown in Fig. 460. The film drive which is carried out by a synchronous motor ensures that exactly 25 pictures per second pass across the scanning point. The correct phase for the timing impulse is adjusted by a simple mechanical arrangement. The compensating time-base circuit superimposes a linear time deflection in such a direction and of such amplitude that the movement of the film is exactly compensated. The return stroke of this

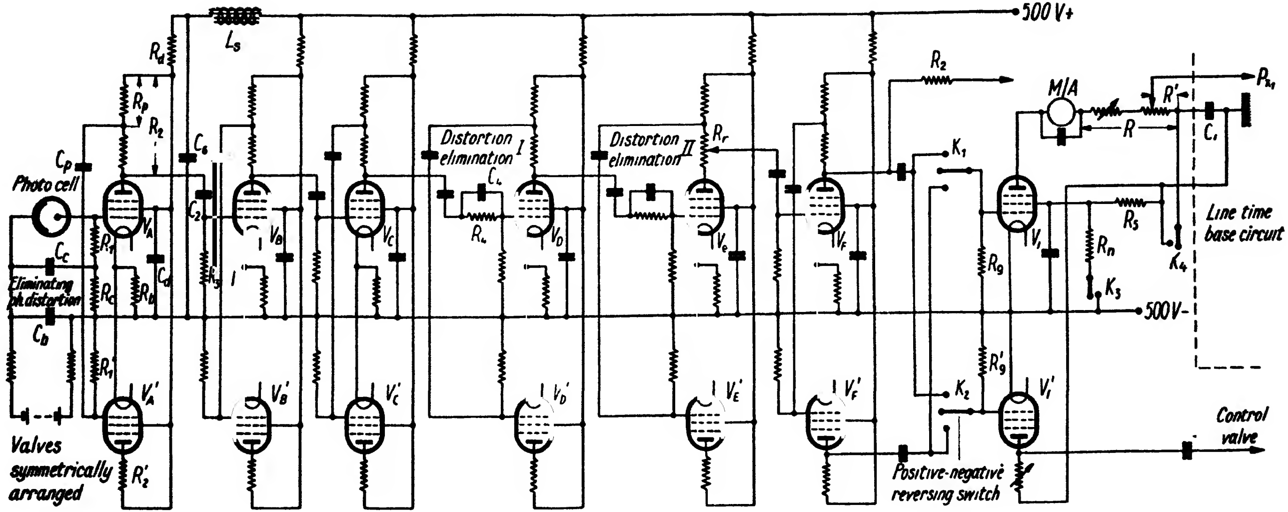

FIG. 461. PHOTO-CELL AMPLIFIER CIRCUIT

deflection is synchronized with the timing device by the aid of condenser C_{912}.

In order to secure control of the picture at the transmitter in spite of the compensating device, a control valve is connected in parallel with the transmitting valve but using a separate potentiometer for the bias potential. The control valve therefore receives the line and picture voltages but not the compensation voltage.

The resistance R_{80} does not serve only to limit the current of the thyratron discharge, but is also intended to prevent a line discharge taking place during a "picture" discharge. The picture return sweep in this way takes place at the edge of the picture. Finally, in the circuit shown in Fig. 460 an important part is played by the resistance R_s and condenser C_s, which are connected to the screen grid of the line charging valve. These ensure that the same mean anode current flows in the valve V_1 independently of the mean brightness of the picture being transmitted, so that a picture is always scanned as a whole in the same constant time. This process involves attenuation of very low frequencies at this point, similar to the author's old arrangement discussed above (Fig. 459).

The photo-cell amplifier also shows a large number of unique features which warrant a detailed discussion, being all the more important because the methods used are in no way limited to amplifiers for transmitters using velocity modulation.

The circuit of the photo-cell amplifier is given in full detail in Fig. 461. The use of high slope valves in combination with relatively low anode resistances and the elimination of anode feed-back by the aid of a screen grid provides aperiodic amplification of the high frequencies of present-day practice. The amplifier must compensate for two sources of frequency distortion which may exist at the input side—

1. That resulting possibly from the effect of phosphorescence on the screen of the transmitting tube.

2. That caused by a high resistance coupling to the photo-cell.

The distortion eliminating stages are arranged in the amplifier after high preliminary amplification between the valves V_E and V_F. The circuit for correcting distortion is shown separately for clearness in Fig. 462. This compensating circuit is based on the fact that at very high frequencies almost the entire anode voltage of the previous stage reaches the grid of the

following valve, while at medium and low frequencies only a small portion of the voltage generally, corresponding to the value of the resistance present, reaches the grid. The resistance R_4 is large compared with the resistance R_3.

The special advantage of this correcting circuit is that the small capacitance C_4 can be made variable and the amount of correction consequently adjusted without the voltage amplification at the same time being affected in the lower frequency range.

In order to keep down the level of the Schröt disturbance, the value of the coupling resistances to the photo-cell must be as high as possible. That part of the noise level due to the Schröt effect is reduced to a minimum by the choice

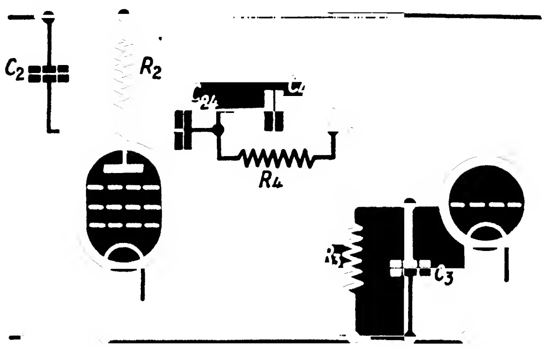

FIG. 462. CIRCUIT FOR ELIMINATING DISTORTION

of high coupling resistances, and can only be reduced still further by reducing the input capacitance. The correction of frequency distortion which originates in the high-coupling resistances is carried out in the second correcting stage mentioned above. Various devices are used in the photo-cell amplifier to secure good performance and an efficient amplification curve over the range of very low frequencies. The coupling condensers between the various stages of amplification are made so large that the time constants of the grid circuits amount to several seconds. The tendency to relaxation oscillations which is otherwise unavoidable with such high values is prevented by the use of valves arranged symmetrically in each stage. These valves again are controlled by a voltage tapped off the anode resistance of the main stages, and their only function is to keep alternating currents away from the decoupling condensers. Only in the output stages the symmetrical

valve is employed in order to carry out the switching over from positive to negative, and vice versa, without altering the amplification. In spite of careful design of the grid capacitances, phase variation in the low frequency range has proved necessary and this has been accomplished by inserting an additional high resistance in series with the coupling resistance of the photo-cell. Except in the very low frequency range this can be considered as being shorted by the capacitance C_c.

If a satisfactory velocity modulated picture appears on the fluorescent screen of the transmitter tube, and an enlarged and contrasty image of it on the control tube, then the next problem is to find the point in the whole circuit of the transmitter set from which to take the frequencies to be conducted to the transmitter. A few years ago it was decided, as a result of Thun's suggestions, to transmit the modulated saw-tooth voltage of the line time circuit of the transmitter. Such a procedure leads to disadvantages of a very serious nature to which the author has already drawn attention. Even if the short wave transmitter is modulated to a very high degree, the modulation corresponding to a single picture point is very small. The details of the picture are therefore seriously affected even by feeble disturbances. In solving this difficulty, Bedford and Puckle indicate a new method which in theory, at least, is extremely interesting. In this connexion, reference may be made to the diagram of Fig. 460. The voltage on the condenser C_1 is received from the signal at the grid of valve V_1 by a kind of integration process which indicates that the higher frequency components are reduced. In the sense of the velocity modulation method, this does not mean that distortion occurs, but that as the field strength of the receiver falls slowly, the higher frequencies, i.e. the picture details drop below the noise level. In order to overcome these difficulties, the voltage transmitted is formed of two components, directly superimposed on one another, viz. one voltage proportional to the displacement and one proportional to the velocity of the cathode-ray scanning. The introduction of the resistance R in Fig. 460 makes the tapping off of such a voltage quite simple. The voltage on the capacitance C_1 at any instant corresponds to the ray displacement, and the voltage across the resistance in series with it to the ray velocity. At the receiver end, both components must again be separated, so that they can perform their respective functions, i.e.

displacement and contrast. This separation, which is only possible on account of the fact that one component is related to the other in a simple way, is effected by means of the circuit shown diagrammatically in Fig. 463.

In this arrangement V is a valve of high internal resistance with an anode resistance R_o, which is bridged to earth through the series connexion of condenser C, and small resistance R' which at the moment is small enough to ignore. As the time constants CR_c at the receiver end are made equal to the time constants C_1R_0 of the transmitter the ratio of the amplitudes of the displacement and velocity components can be brought to any desired value. The advantages in forming the voltage to be transmitted which has just been discussed, lies in the process of reception. In particular, the transmission of synchronizing impulses at the end of a line is unnecessary, as distinct from the usual process which to-day is familiarly known as the *intensity* process. All the advantages of complete transmission of the modulated line discharge voltages are retained, and the disadvantages discussed are excluded. On the transmission side the conditions are such that the resulting degree of modulation is almost, if not entirely, constant.

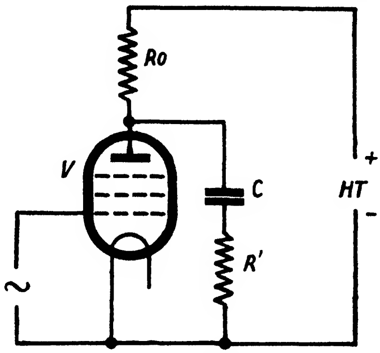

FIG. 463. PRINCIPLE OF FREQUENCY FILTER

The television portion of the complete receiver is illustrated in Fig. 464. It comprises the frequency filter discussed, for separating the displacement and velocity components, a line voltage amplifier to secure sufficient voltage output, a picture time-base circuit, and an amplifier for securing contrast from the velocity components. The symmetrical stage at the input serves to avoid distortion at very low frequencies. The neon stabilizer stage in the anode circuit of the first valve is provided to reduce the effect of mains voltage fluctuations which is very serious here. The first dual stage controls a second similar stage in the usual push-pull arrangement. The line voltage for the receiver tube is taken between the anodes of the second dual stage. The anode circuits of this stage

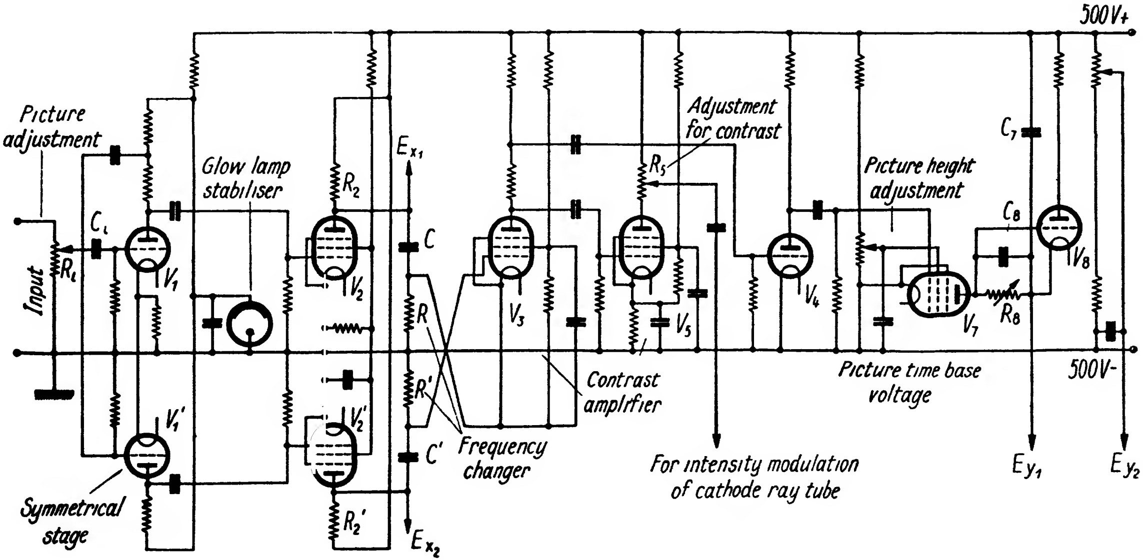

FIG. 464. DIAGRAM OF THE TIME BASE CIRCUITS OF THE RECEIVER

contain the frequency filter which has already been discussed with reference to Fig. 463, the time constant of which must be adjusted to be the same as the time constant of the corresponding circuit in the transmitter. Here, again, is seen a special advantage of separating the two components. For instance, R_2 and R_2' can be made relatively large (50 000 ohms) which, in view of the detrimental effect to high frequencies, would not be possible in the transmission of modulated line discharge voltages only. In the case under discussion it is necessary to reduce the high frequencies at this point, and this can be done by increasing the valve capacitances through the condensers C and C_1. The high anode resistance at this point makes high voltage amplification possible and gives rise to practically a straight line characteristic. A small voltage corresponding to the velocity component appears across the resistances R and R_1. By means of two amplifying valves V_3 and V_5 this voltage is increased to an amplitude sufficient for superimposing on the intensity control of the receiving valve. The first valve of the contrast amplifier controls simultaneously the next valve V_4, and with it the interconnected discharge circuit for the picture voltage. This set corresponds exactly to the picture discharge circuit of the transmitter discussed (Fig. 460). The back-coupling at the end of each line produces current impulses in the valve V_8, which maintains the bias of the thyratron V_7. The discontinuity of the line fly-back at the end of the picture causes a short interruption of the bias on the thyratron grid, and therefore of the discharge, which is set by the time constant C_8R_8.

The operation of the receiver is relatively simple. The voltage regulator R_1 at the input side should be adjusted so that the desired width of picture is obtained. Then the screen-grid voltage of the valve V_7 should be adjusted so that the required height of picture is obtained. Operation of the synchronizing process is unnecessary; the potentiometer R_5 alone should be altered until the required contrast is obtained.

The procedure for adjustment mentioned can, of course, only be carried out as long as a transmission is being received. It might be feared that if a transmission is not taking place, the ray would remain stationary and so destroy the screen. This cannot, however, happen in practice, because as soon as transmission ceases, breakdown of the bias at C_8R_8 and at valve V_7 causes the condenser C_7 to be charged to a high value

and discharged periodically through the thyratron. A vertical stroke then appears on the screen. An untouched photograph

FIG. 465. 120-LINE PICTURE WITH SUPERIMPOSED INTENSITY AND VELOCITY MODULATION
(*Bedford and Puckle*, AUTUMN, 1933)

of a 120-line picture transmitted by the arrangement to which reference has been made is shown in Fig. 465.

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